Progress on the Lithium EUV Source for HVM

Sematech Intl. EUVL Symposium, Toyama, 6-10 Oct. 2013

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Contents of Talk

Lithium Physics: reason for high efficiency

Lithium Test Source Performance

Multiplex Architecture: from individual lamp to system
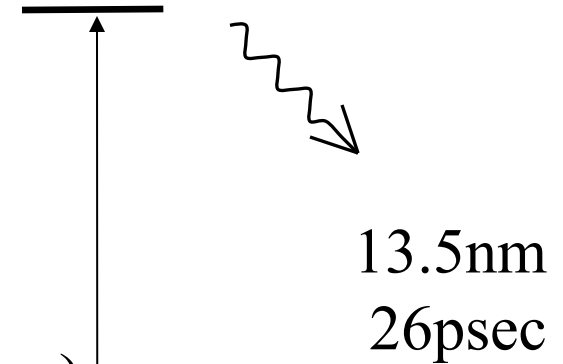
Electrode Thermal Management
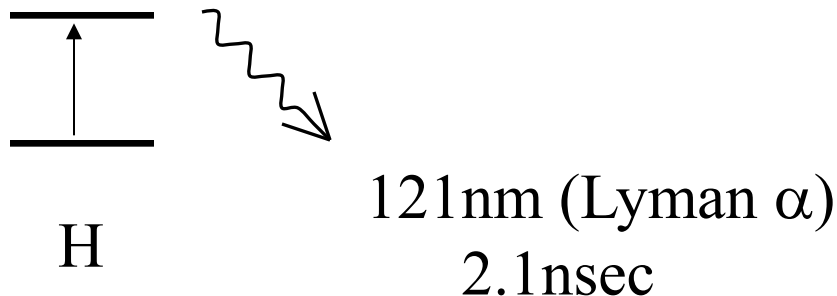
Scaling to >500W

Cost of Ownership

Summary

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Contents of Talk

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Hydrogen-like lithium is a souped-up hydrogen atom with Z=3

Like sodium lamp and mercury lamp, efficiency is due to a resonance transition

$$Li^{2+} ground + e^-(fast) \rightarrow Li^{2+} resonance + e^-(slow)$$

$$Li^{2+} resonance \rightarrow Li^{2+} ground + h\nu(13.5nm)$$

13.5nm
26psec

121nm (Lyman α)
2.1nsec

H

Li^{2+}

Li^{2+} is dominant species for electron temperature range 8 - 20eV

Fractional abundance

Li^{2+} (hydrogen-like lithium)

Li^{+}

LOCH *et al.*
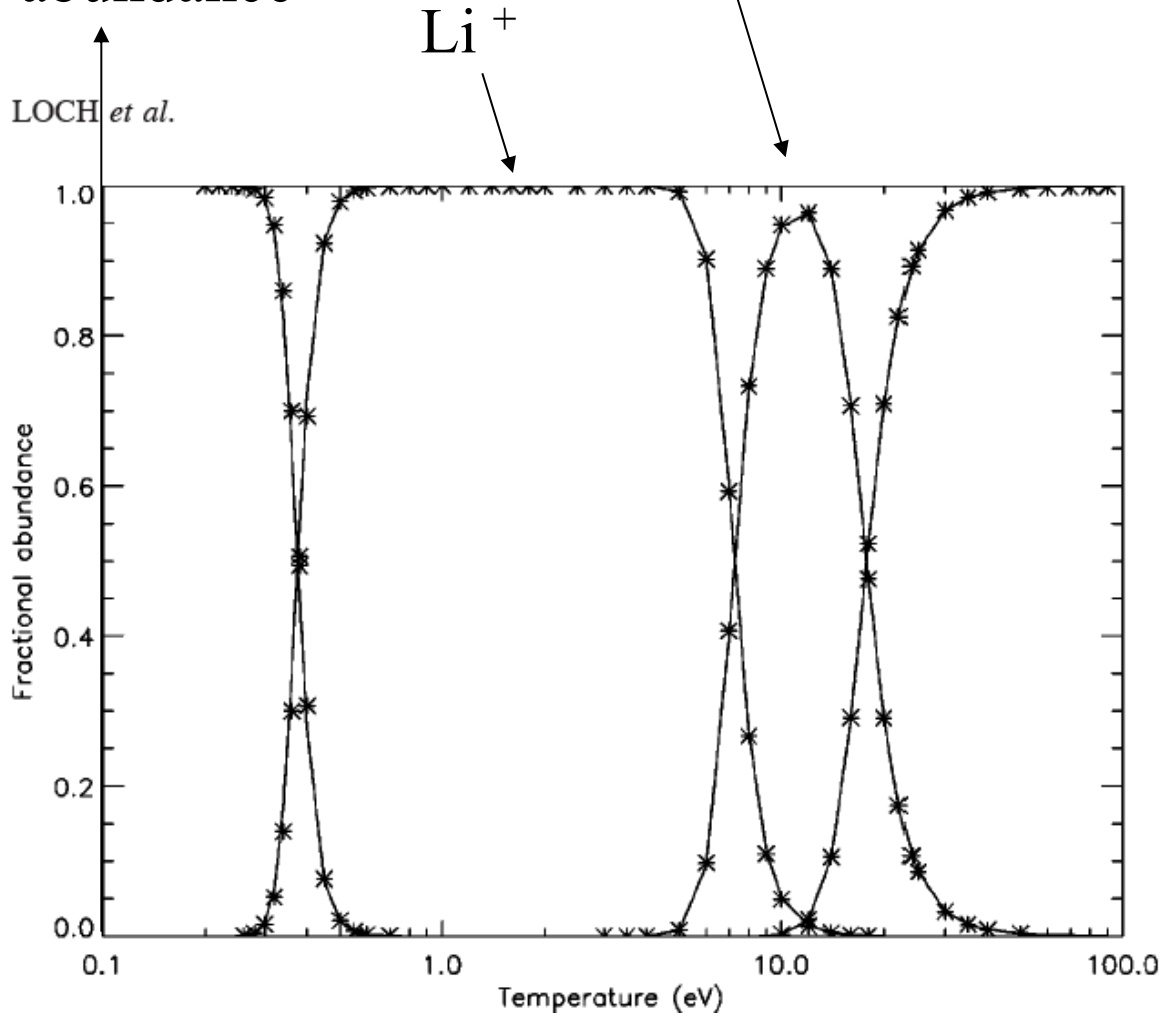
FIG. 1. Ionization balance at $N_e = 10^{14}$ cm^{-3} for the ADAS-1 and LANL-1 calculations. The solid curve shows the ADAS-1 results and the stars show the LANL-1 results. Note that the peak at lowest temperature corresponds to neutral lithium, the one centered at 2 eV is the He-like stage, the one at about 10 eV is the H-like stage, and the last peak is the bare nucleus.

electron temperature (eV)

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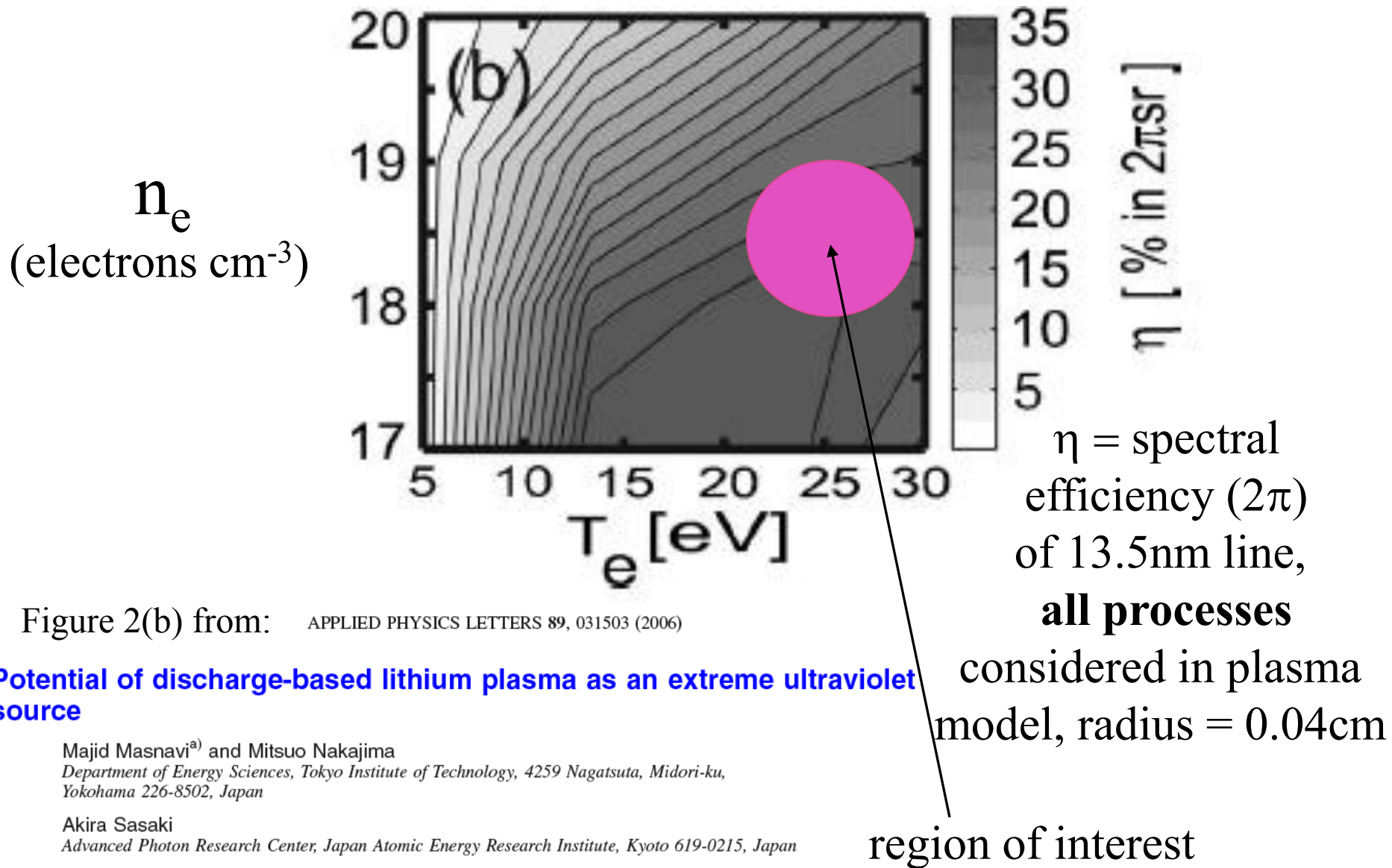# In a "steady state pinch" lithium spectral efficiency -->35%

n_e
(electrons cm^{-3})

η = spectral efficiency (2π) of 13.5nm line, **all processes** considered in plasma model, radius = 0.04cm

Figure 2(b) from:

Potential of discharge-based lithium plasma as an extreme ultraviolet source

Majid Masnavi[a)] and Mitsuo Nakajima
Department of Energy Sciences, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

Akira Sasaki
Advanced Photon Research Center, Japan Atomic Energy Research Institute, Kyoto 619-0215, Japan
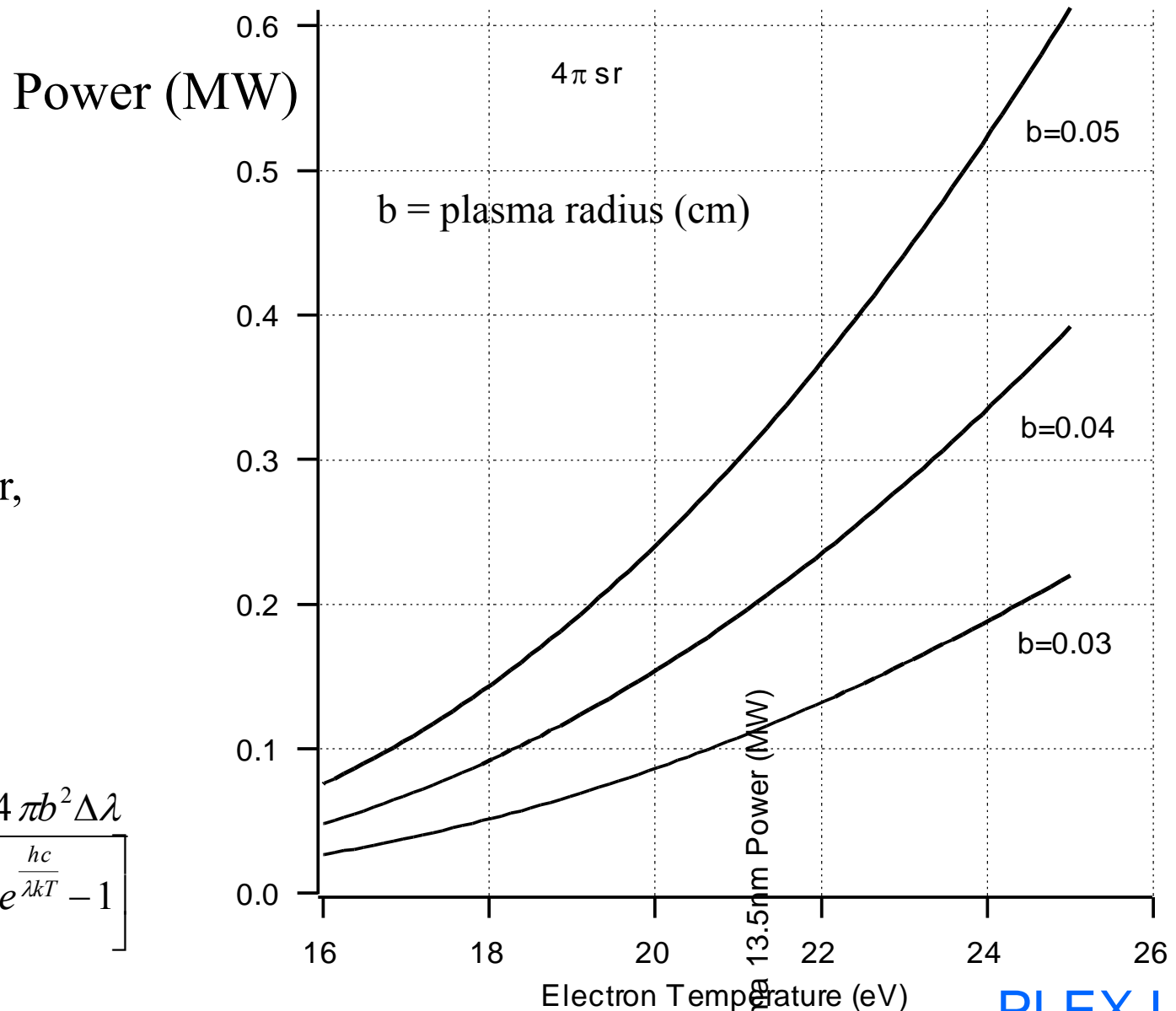
Eiki Hotta and Kazuhiko Horioka
Department of Energy Sciences, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

region of interest

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Radiation trapping (Planck limit) sets surface brightness

Power (MW)

4π sr

b = plasma radius (cm)

b=0.05

b=0.04

b=0.03

Lithium
$\Delta\lambda = 0.009$nm
mainly Doppler,
line-broadened
by radiation
diffusion

$$P_{\Delta\lambda}(b,T) = \frac{2\pi hc^2}{\lambda^5} \frac{4\pi b^2 \Delta\lambda}{\left[e^{\frac{hc}{\lambda kT}} - 1\right]}$$

13.5nm Power (MW)

Electron Temperature (eV)

16   18   20   22   24   26

0.0   0.1   0.2   0.3   0.4   0.5   0.6

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So, just how much EUV power can theoretically be produced from a quasi-steady spherical lithium plasma of 0.035cm radius (700μm diameter) at 25eV?

From Planck limit, at 25eV, **P = 0.175MW into 2π**

With the demonstrated **3μsec** capability (electrode heating OK)

==> E = 0.52J/pulse into 2π, per lamp

i.e. **One lamp at 1kHz** (discussed later) should give **520W** at source.

Power scaling is planned via **multiplexing** of 8 simple lithium lamps

Intermediate focus power is reduced to **500W** by various factors.

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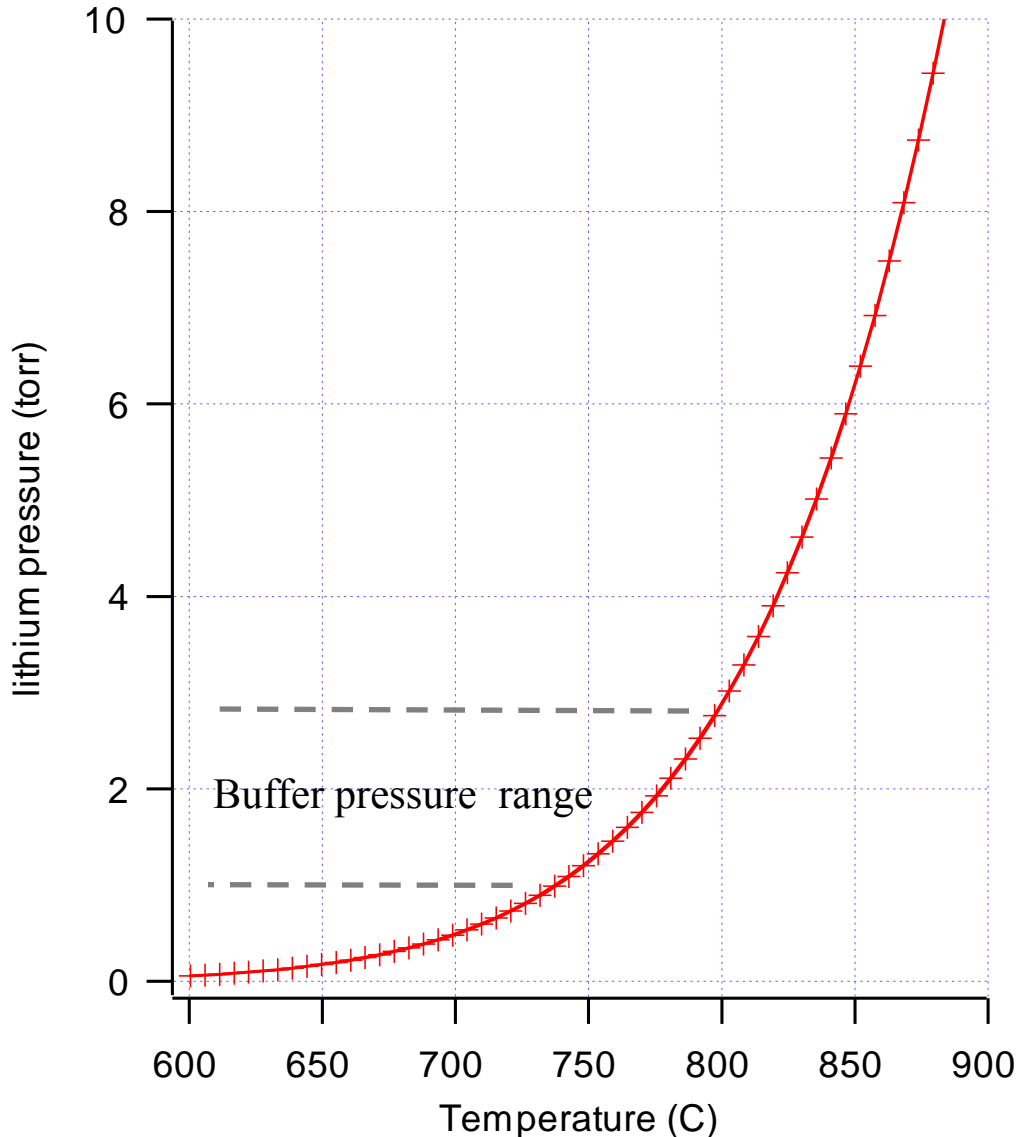PLEX LLC

First, the technology:

Lithium floating in paraffin, from Wikipedia

Reacts with moisture in air rapidly, and oxygen, nitrogen more slowly
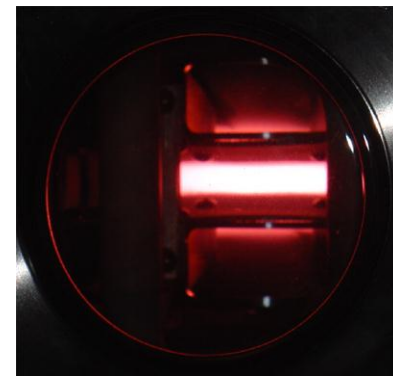
Can be contained at 750C in molybdenum, stainless etc. But no ceramics.

Lithium is used as a gas within the Z-pinch

Lithium has a high vapor pressure at modest temperature

A lithium discharge apparatus runs at 750C, 'orange' heat
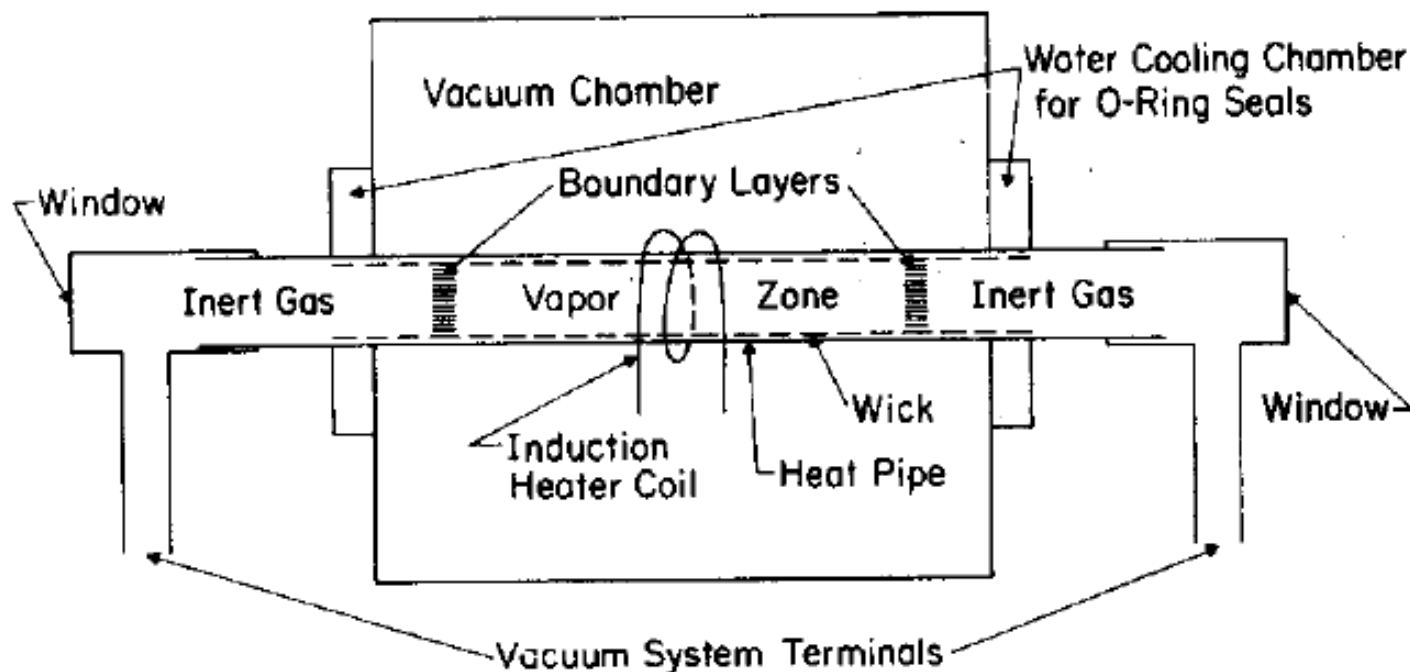
Lithium heat pipe technology is mature

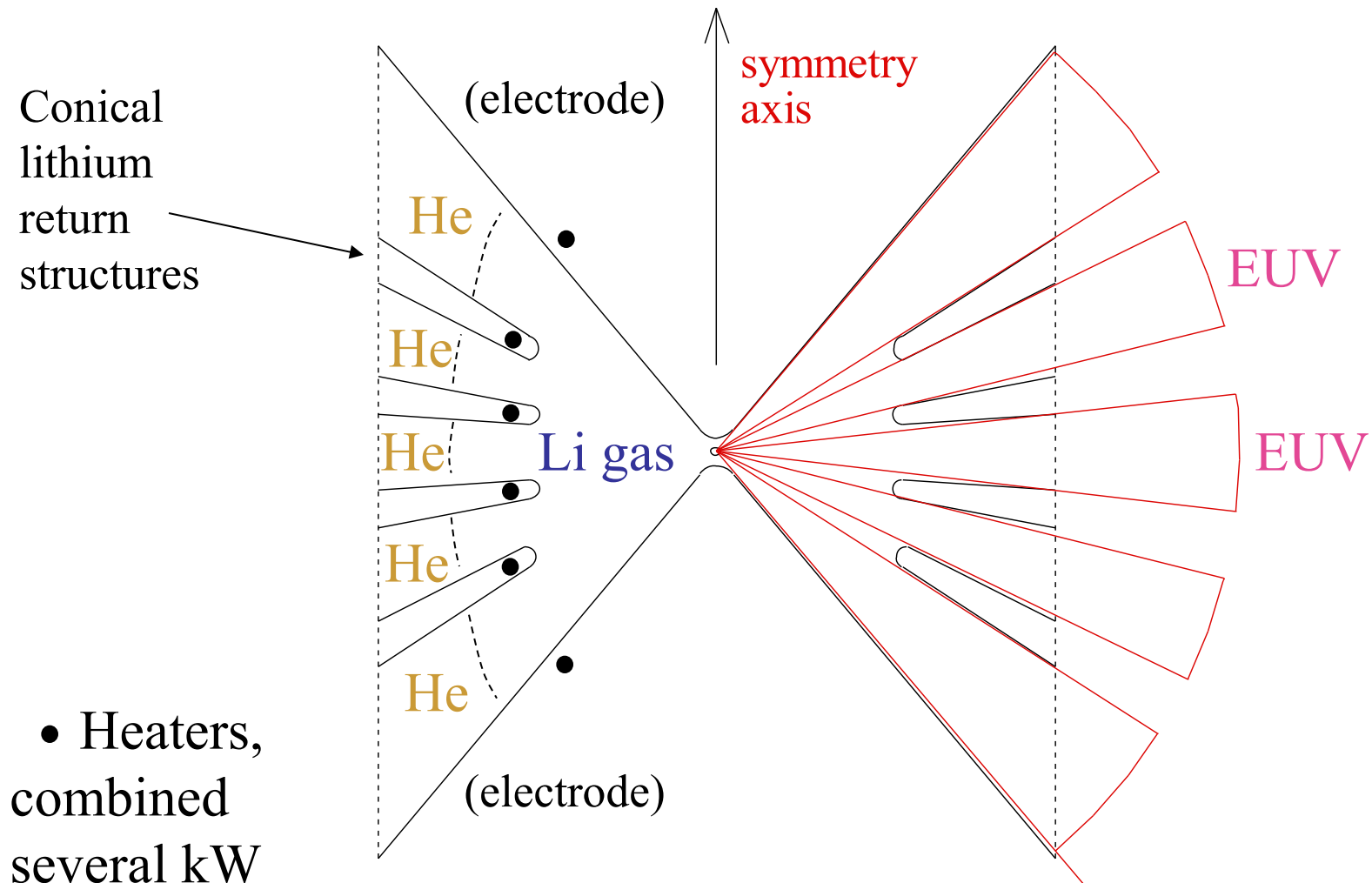FIG. 1. Schematic arrangement of the heat-pipe oven.

Heat-Pipe Oven: A New, Well-Defined Metal Vapor Device for Spectroscopic Measurements*

C. R. VIDAL AND J. COOPER†

National Bureau of Standards, Boulder, Colorado 80302

(Received 13 February 1969)

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We developed a wide angle buffer gas heat pipe discharge

Conical lithium return structures

(electrode)

symmetry axis

He

He

He

He

He

Li gas

(electrode)

EUV

EUV

• Heaters, combined several kW

70% geometrical transmission today. Expect 80%

A key technology advance in lithium handling:

FIGURE 1A

US Patent to issue 2013:

"Induction heated buffer gas heat pipe for use in an extreme ultraviolet source"

Drawing illustrates one of several lithium control surfaces in a source and is not to scale
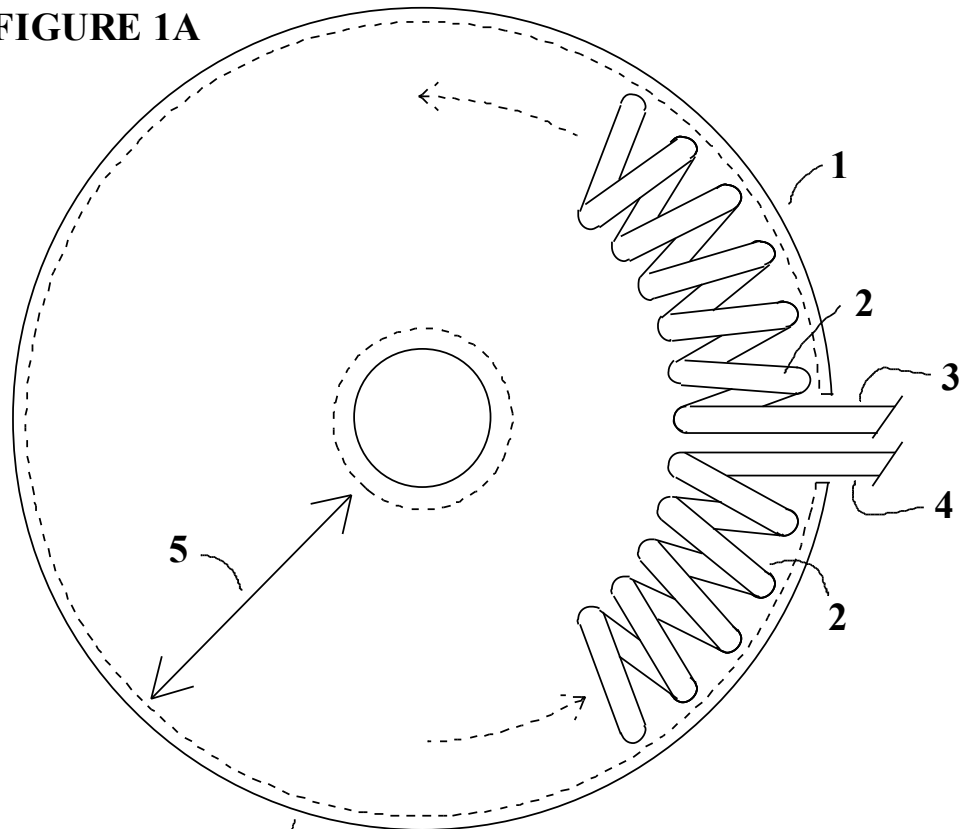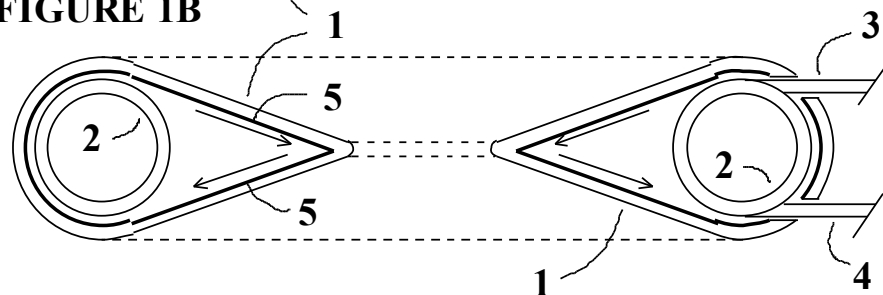
FIGURE 1B

FIGURE 1, parts A and B

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The heat pipe **<u>is</u>** the "debris" barrier!

Li plasma atoms and ions are stopped 5cm from pinch location

He

Li

(re-evaporation)   Li is recycled!   mesh
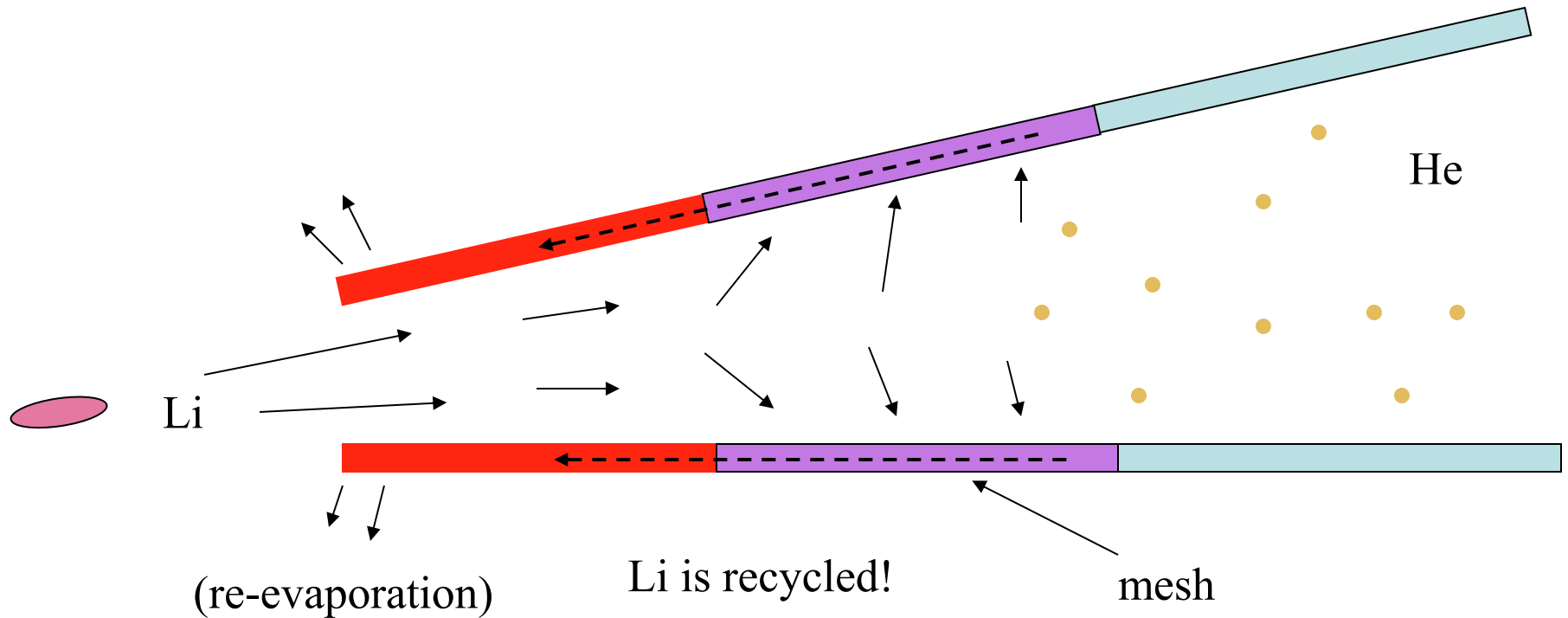
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Lamp is very compact: fits within 20cm diameter chamber

20cm

EUV camera
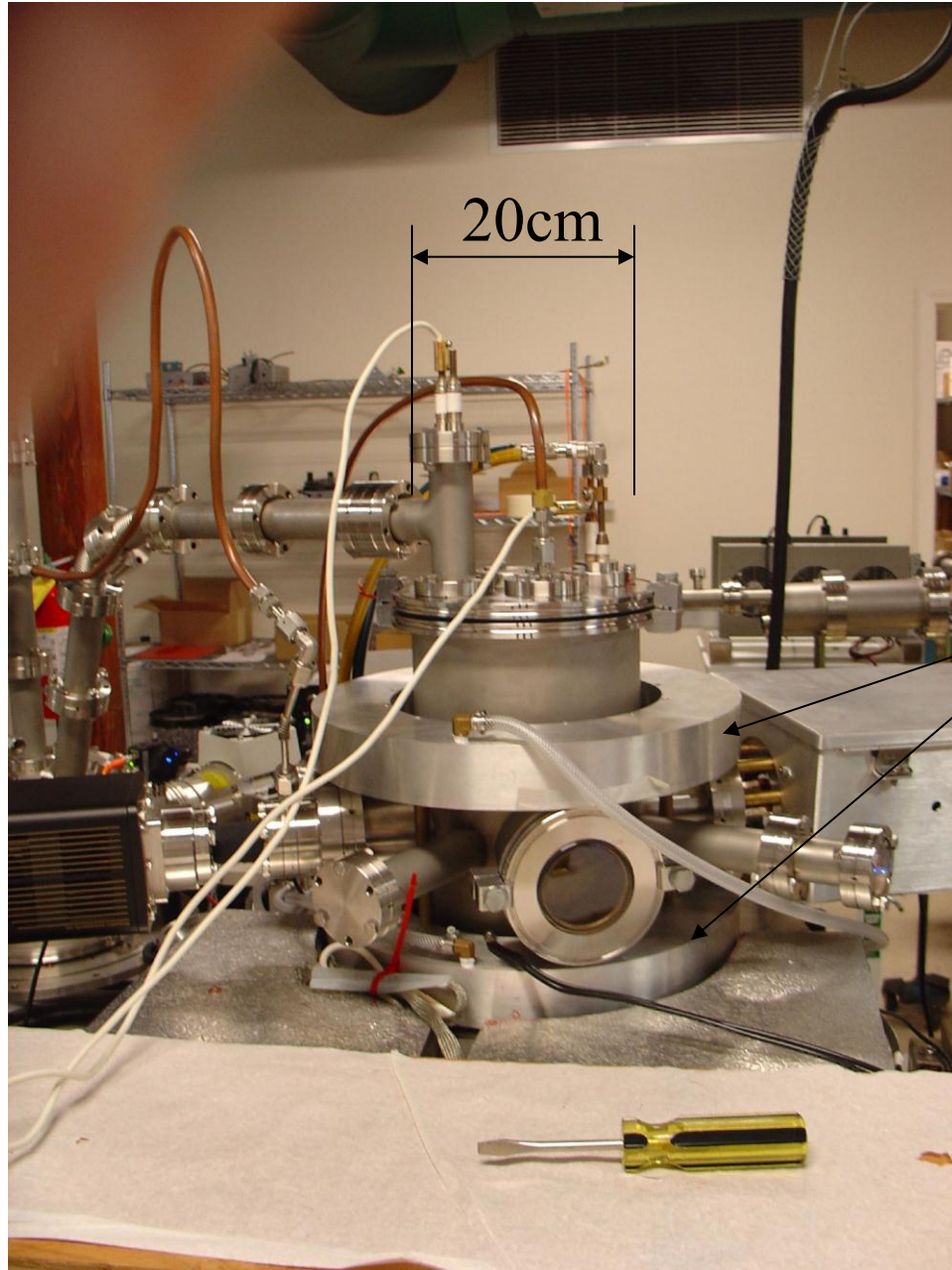
Helmholz coils 0.04T

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B

(Li gas)

Li liquid

E

Symmetry Axis
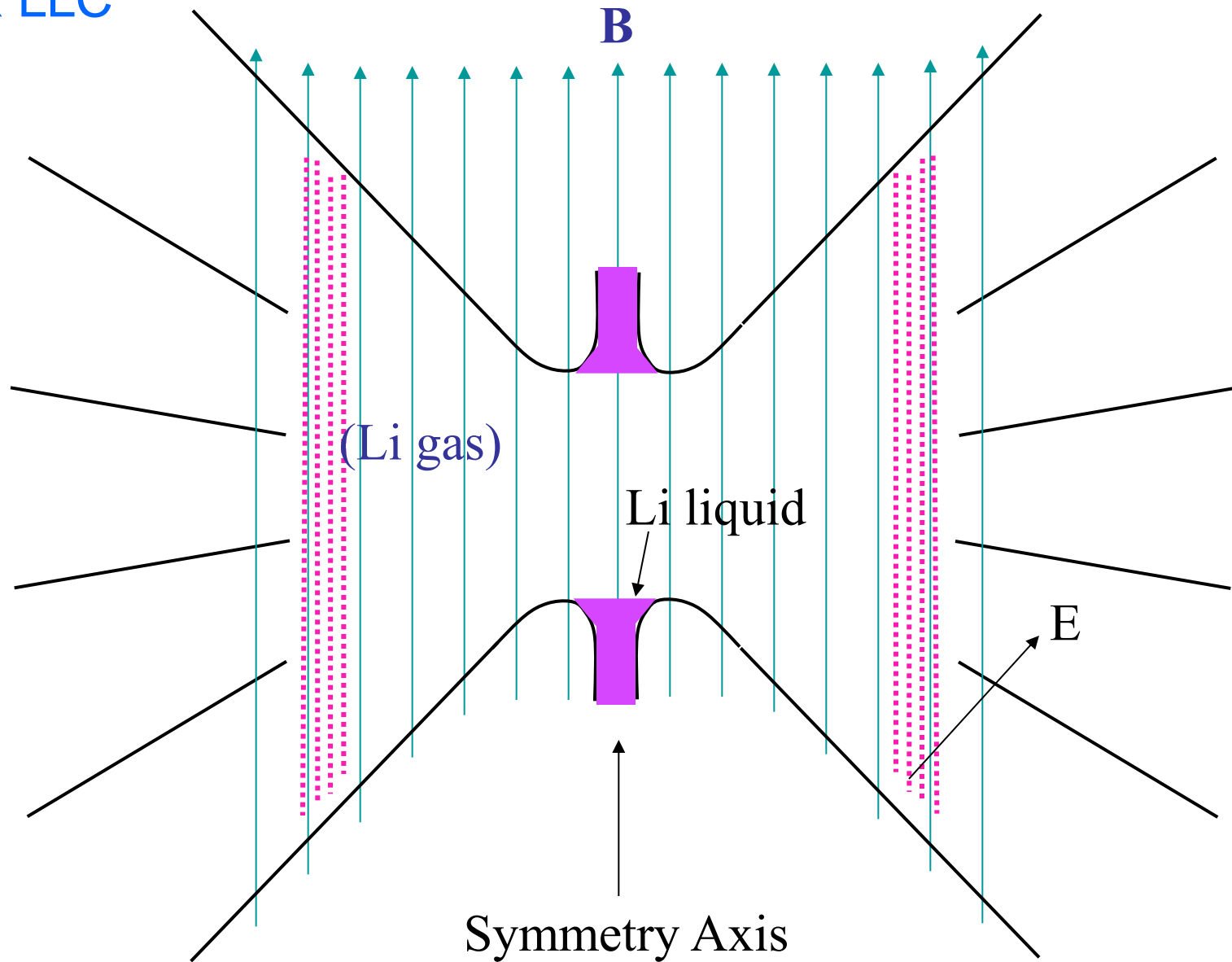
Ignition is via plasma sheet (skin effect) with ExB azimuthal spreading

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B

Symmetry Axis
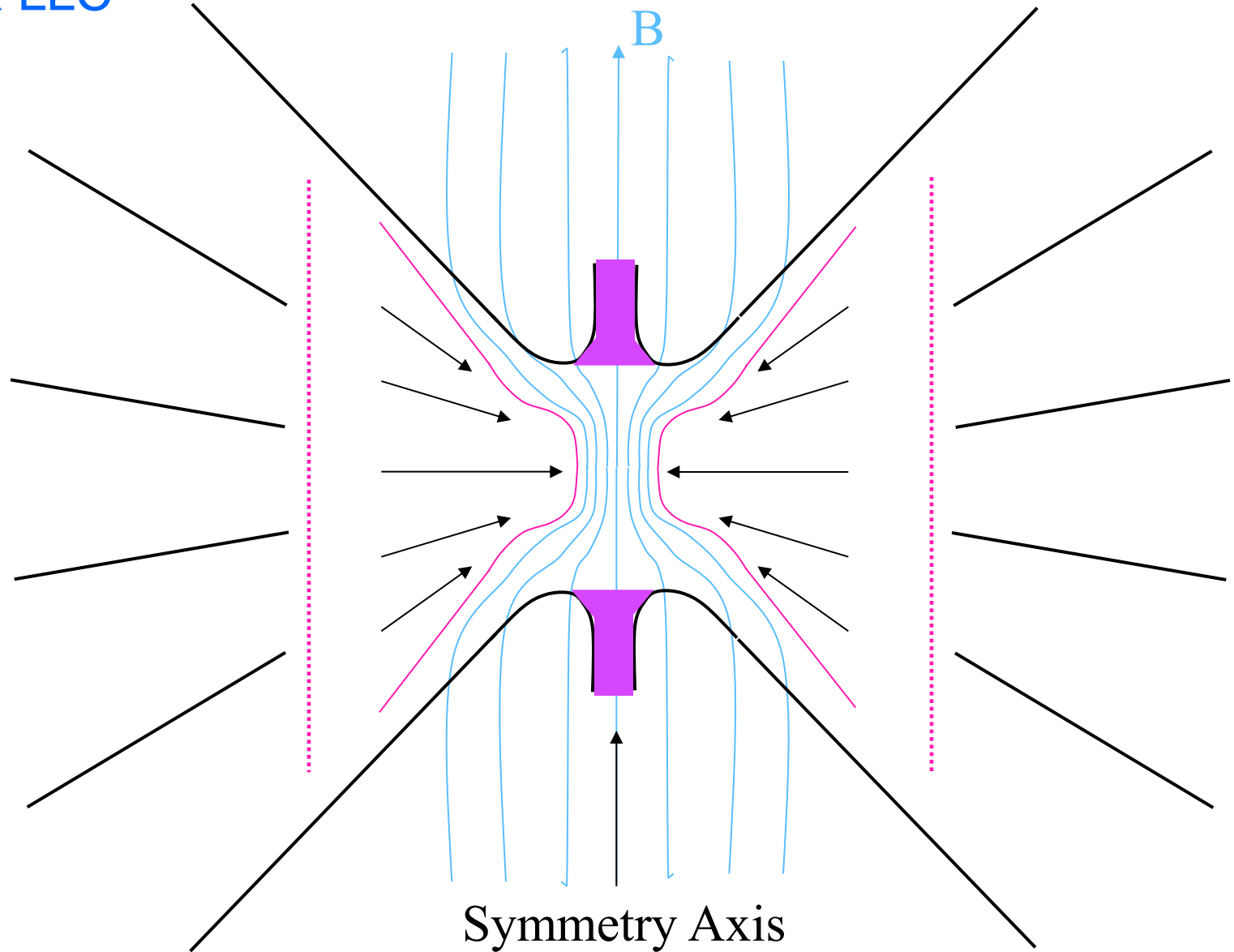
3-D compression pulse guided by electrodes --> high density

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B

Symmetry Axis
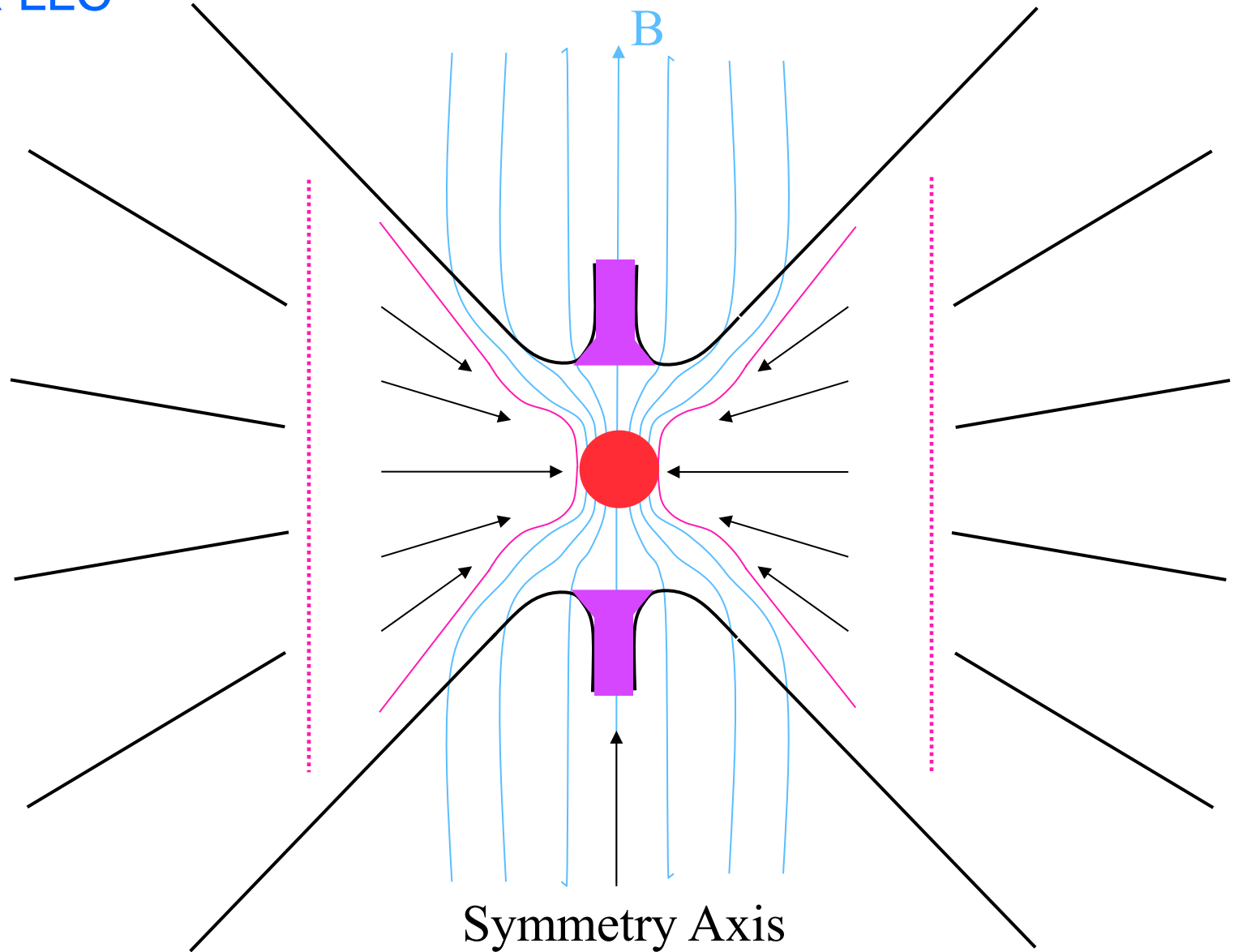
Plasma compresses magnetic field, protecting electrodes
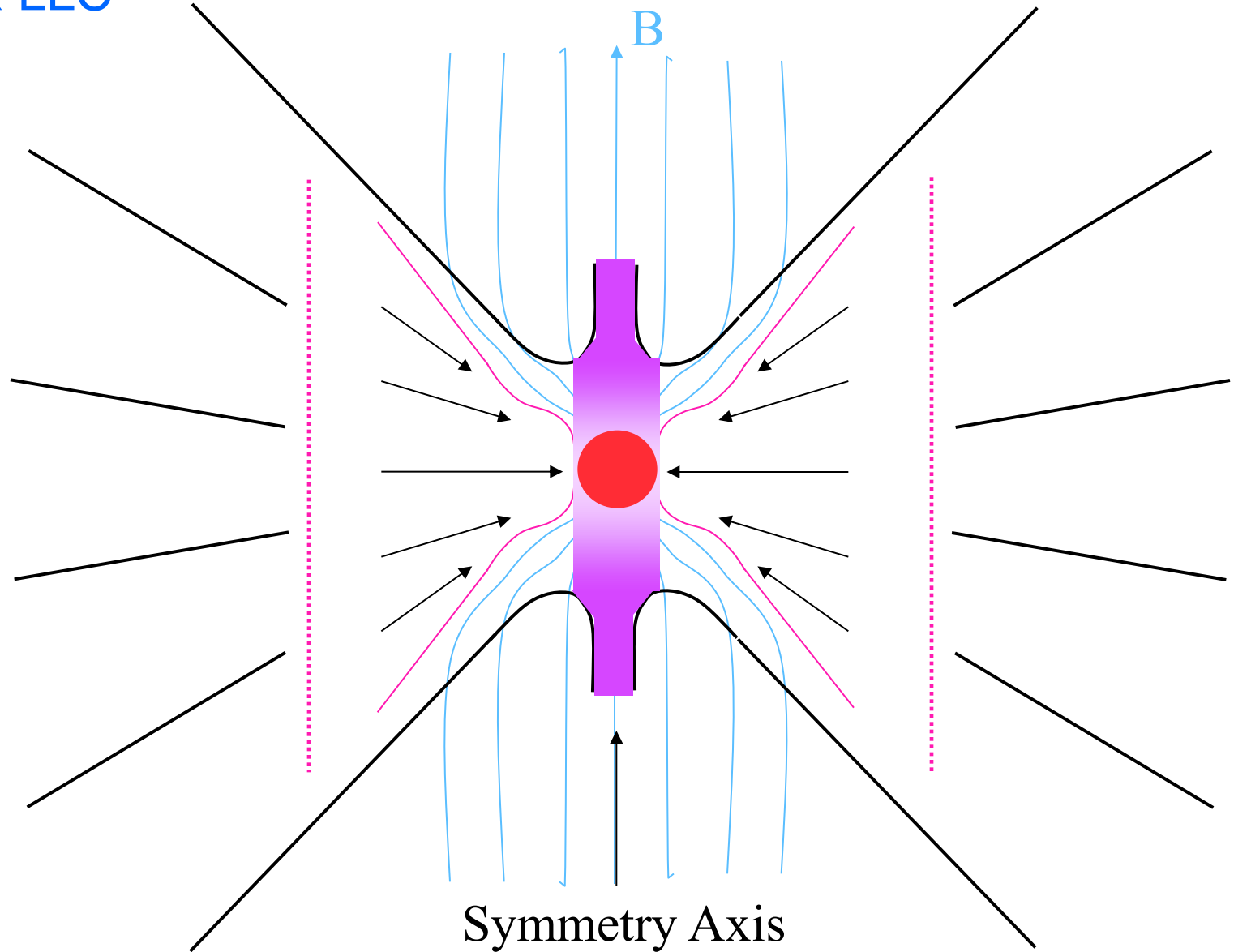
Pinch plasma heat and radiation evaporate more lithium

Plasma Size in 13.5nm light

714 ± 39 μm FWHM

Stability 94μm rms

mean of 15 images
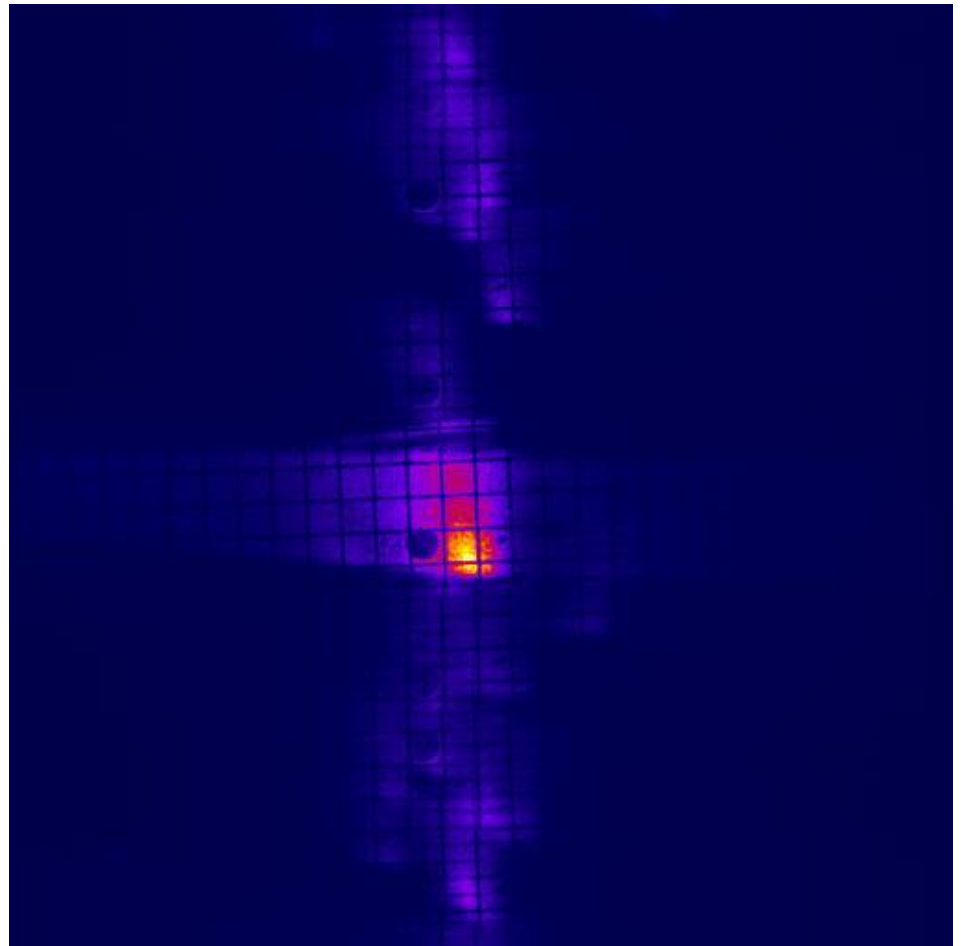
Superposition of 80 pulses at 400Hz in each pinhole camera image

65mJ/pulse/2π sr, 1.2μs FWHM, 3μs total EUV duration

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EUV and Pinch current waveforms
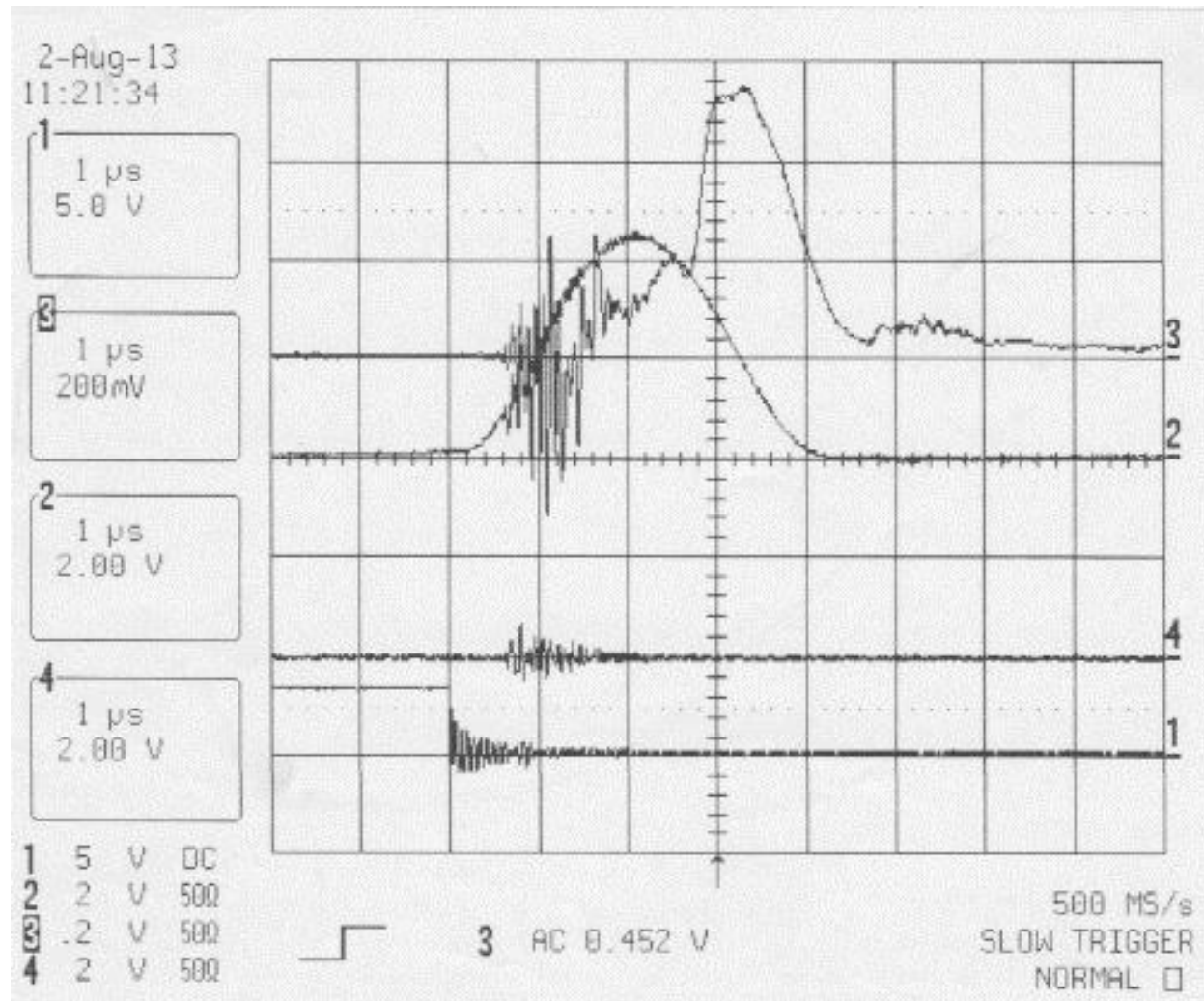
EUV diode

Pinch current
(peak 9.7kA)

1 μsec/div

Peak EUV power (2π) = 46kW, energy 65mJ

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Updated EUV lamp parameters 9-26-13

Steady wetted electrode operation at 400Hz for 30minutes:

65mJ/pulse in-band in 2π steradians

Plasma diameter 714μm ±39μm,   length tunable - presently 1000μm

Plasma centroid stability ± 94μm radially; ±47μm axially

Calculated steady 30W at intermediate focus if eightfold multiplexing at 400Hz

Higher power also achieved at 1kHz for 300sec projects to 80W at IF

Steady source brightness is improved 5X since 2013 SPIE

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Present experimental status compared to theory

EUV output from 1 lamp

From theory slide '8', expect max. of **520mJ** per pulse at **175kW** for **3μsec**

Today, peak power from 700μm source = **46kW** i.e. **26% of max.**

Power gap will be closed via: **a)** increased current; and **b)** higher Li density

In addition, energy gap will be closed via improved EUV waveform
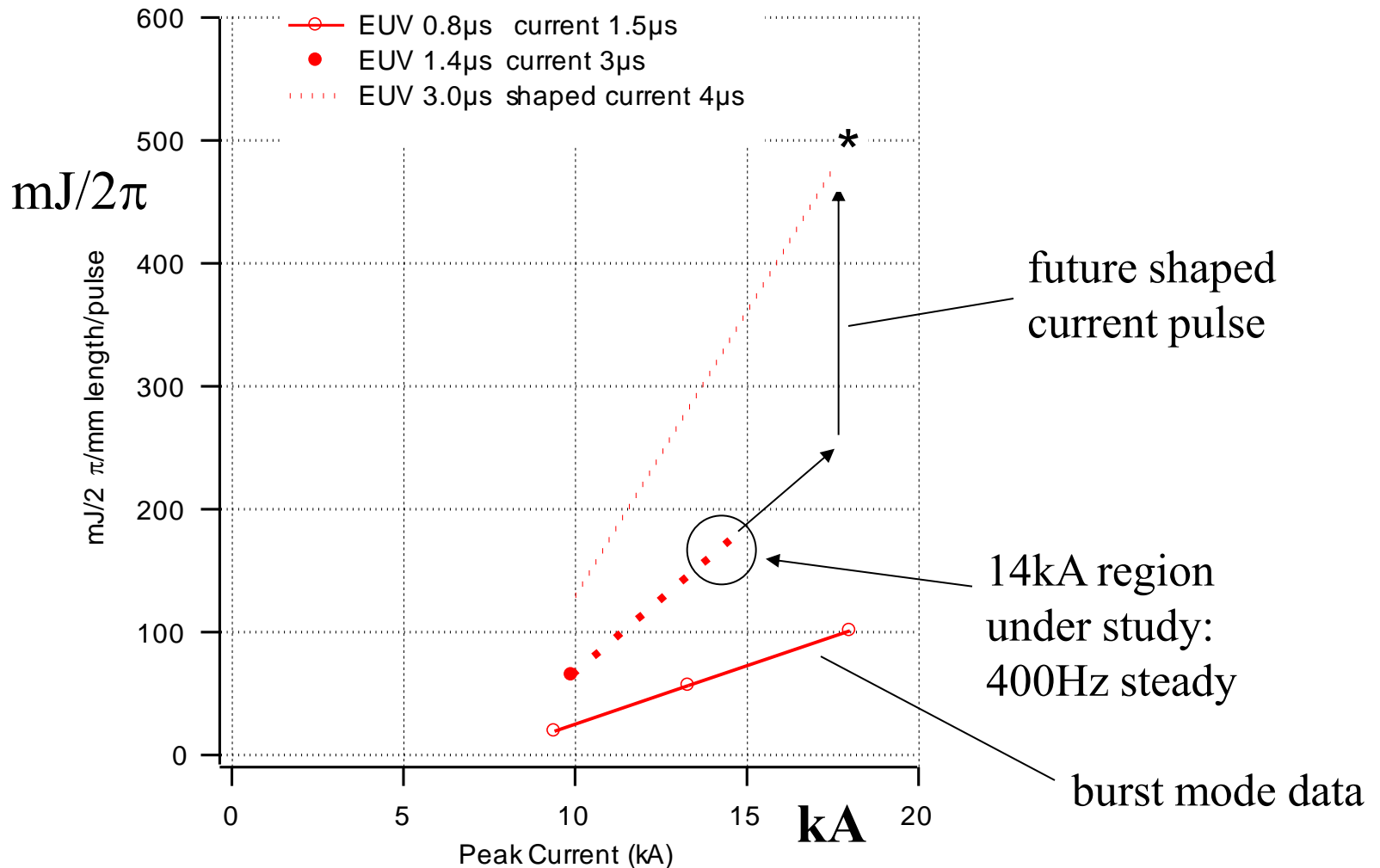
today's EUV waveform

improved waveform for 500mJ
(not to scale)

3μsec

T=25eV

How to get 500mJ

A. More current, because at constant size, plasma density goes as I^2 and excitation power goes as I^4 (more Li also required, as I^2)

B. Shaped current pulse --> 3µs steady EUV

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Compact 1kHz Li lamps may be multiplexed with 85% efficiency

INTERMEDIATE FOCUS

GRAZING INCIDENCE
SPINNING MIRROR
(MAGNETIC BEARINGS)

center grazing incidence
angle = 12.5 deg

210 cm

NESTED COLLECTOR

HELIUM BARRIER (PELLICLE)

FINAL STAGE OF
LAMP DRIVE CIRCUIT

VACUUM VESSEL

LITHIUM EUV "LAMP"

HEATER CIRCUITS

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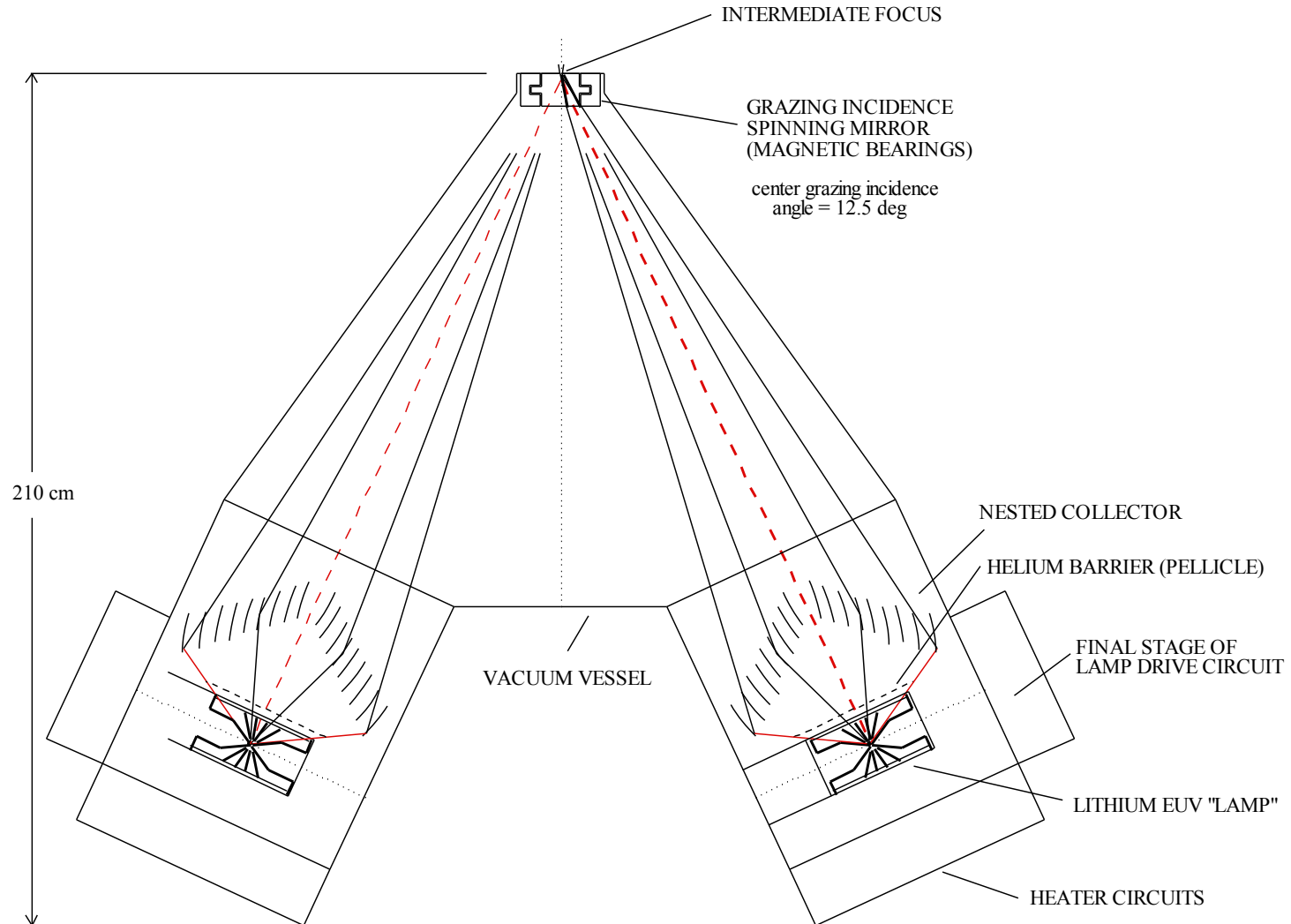
Grazing reflection efficiency is 85% over multiplex angle range

Reflectivity (%)

Grazing incidence angle (deg)

Mo mirror
unpolarized 13.5nm light
rms surface roughness (nm)
△ 0nm
■ 5nm
○ 10nm

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Transmission to IF

INTERMEDIATE FOCUS

(STEPPER)

LITHIUM EUV "LAMP"

GRAZING INCIDENCE
SPINNING MIRROR
(MAGNETIC BEARINGS) $T = 85\%$

center grazing incidence
angle = 12.5 deg

VACUUM

NESTED COLLECTOR   3.2sr, $T = 50\%$, overall 25%

HELIUM BARRIER (PELLICLE)   Pellicle T=90%

HEATER CIRCUITS

FINAL STAGE OF LAMP DRIVE CIRCUIT

Helium region T=82%

Geometrical obscuration T=80%

Multiplexed Lithium system power projects to > 500W

Returning to the 700μm dia., 25eV, 3μsec, <u>1kHz</u> case:

520W into 2π (1 lamp)

$3mm^2$sr etendue ==> >4sr collection possible

Media-Lario grazing incidence collection efficiency 25%

W_{IF} = 520 x 0.8 x 0.82 x 0.9 x 0.25 = 77 Watts per lamp

Multiplex x8 ==> 77 x 8 x 0.85 = **524W (IF) at 8kHz**

Suggestion for lithium source pellicle fabrication

DUV laser

electroless Ni plating -> "honeycomb"

shadow mesh   slab of photo-polymer

backfill, planarize,
then 'ML'
deposition

remove
backfill
then
assemble
segments

"honeycomb"

EUV

'ML'

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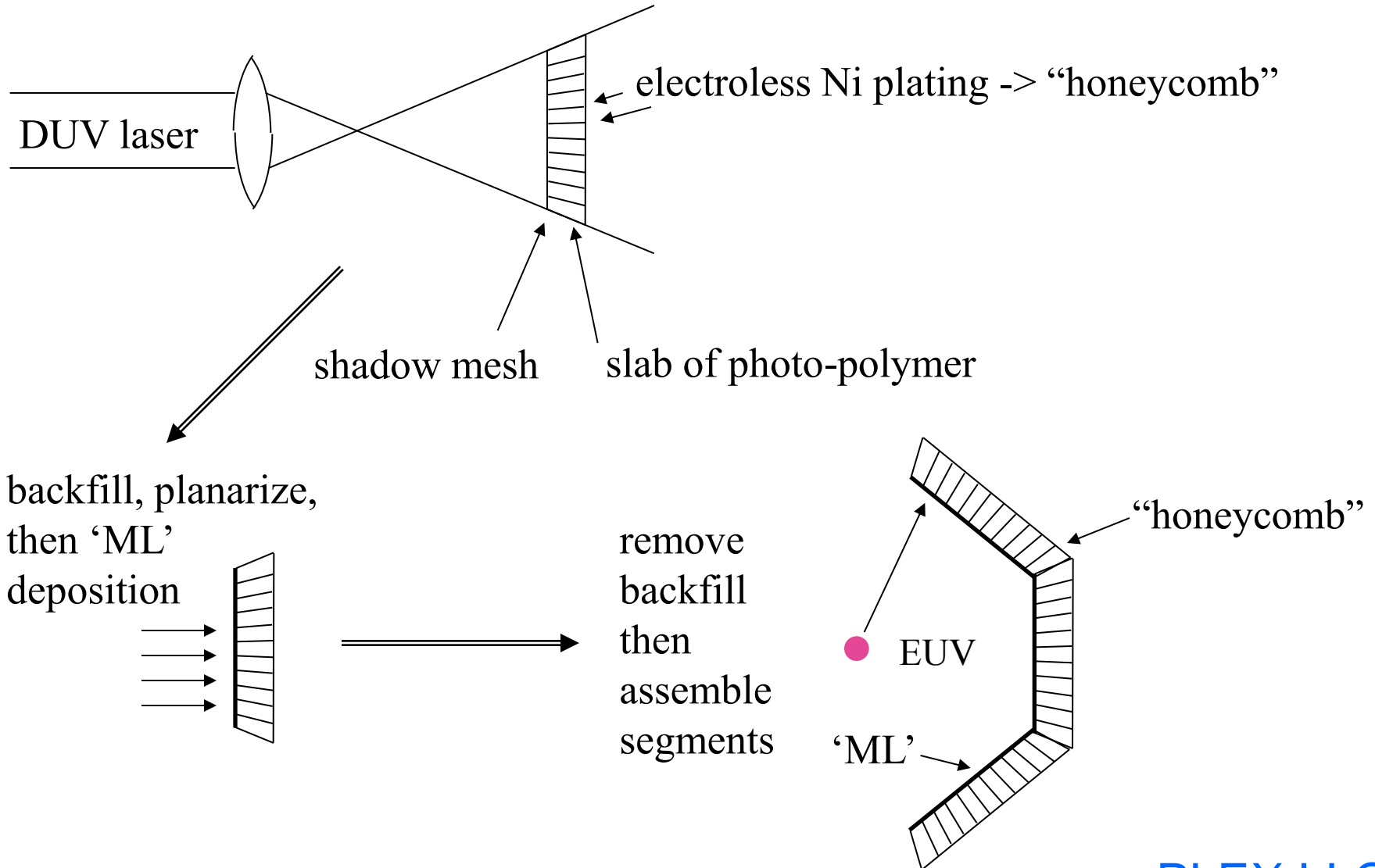
Pellicle Design

Apparently no fast ions, droplets or other particles from source

Thermal load is comparable to mask location loads => type 'ML'
(Scaccabarozzi et al, Proc SPIE 8679, 867904 1-12 (2013))

A robust frame/mesh can be deployed - no imaging concerns

Lithographic electroless Ni plating of honeycomb frame
(Schaedler et al, Science 334, 962-965 (2011)

Planarized, then 'ML' deposited. Expect 90% transmission

"Spherical" shape built from plane hexagonal and pentagonal sub-pellicles

Pellicle development should be started immediately

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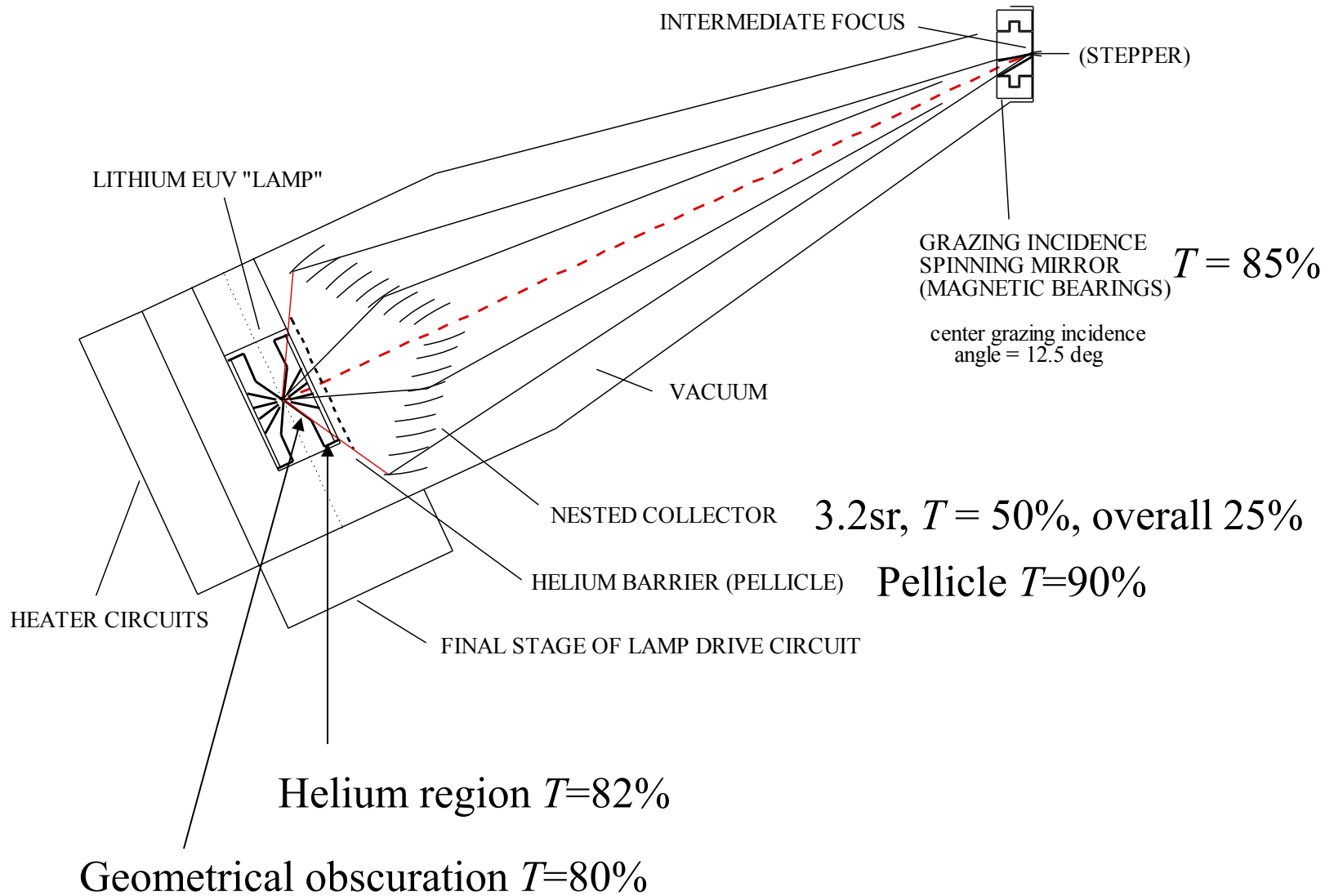PLEX LLC

Electrode life extends to HVM with lithium protection

Each electrode at 1kHz should be designed to last >1billion pulses (i.e. >278 hours continuously). The more the better.

We have developed a lithium-wetted electrode tip

Evaporative cooling capability of Li is huge: 147kJ/mole

500W IF source needs 330W removed from electrode tip - -only 16 mg sec^{-1} flow required/electrode

Tip component is small and easily replaced

The following slides give details:

Lithium phase change cooling is very effective

kW mm^{-2}

$$W(T) = \frac{7.2x10^{-4}}{\sqrt{T}} \exp(1.5x10^{-2}T) \quad \text{W cm}^{-2}$$

$(T \deg K)$

ºC

Phase Change Cooling Capacity of Lithium (kW mm^{-2})

Liquid Lithium Temperature (ºC)

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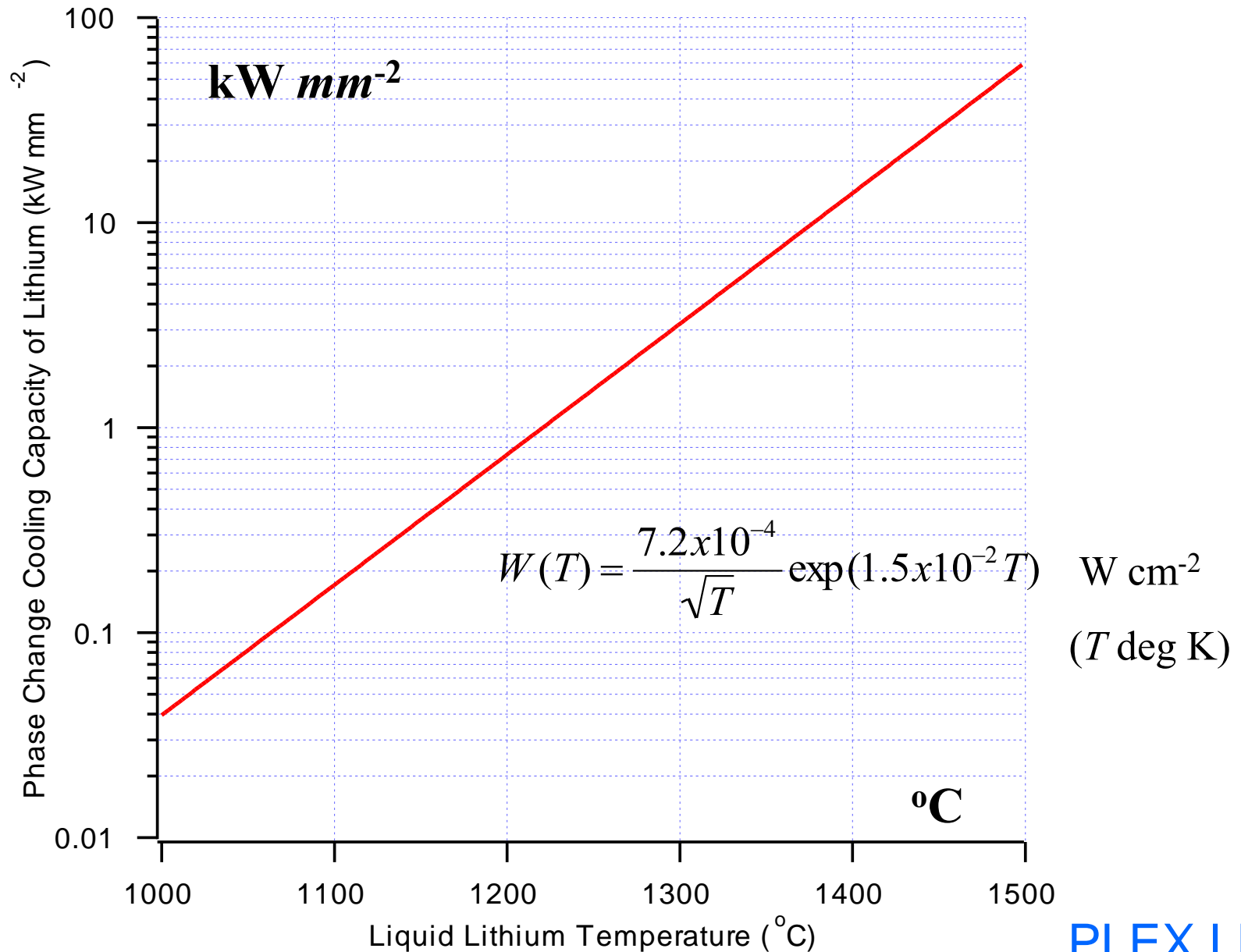
Lithium-wetted electrode tips: plasma heat load

Plasma thermal conduction

EUV

Li flow

r_P

δ

Current path
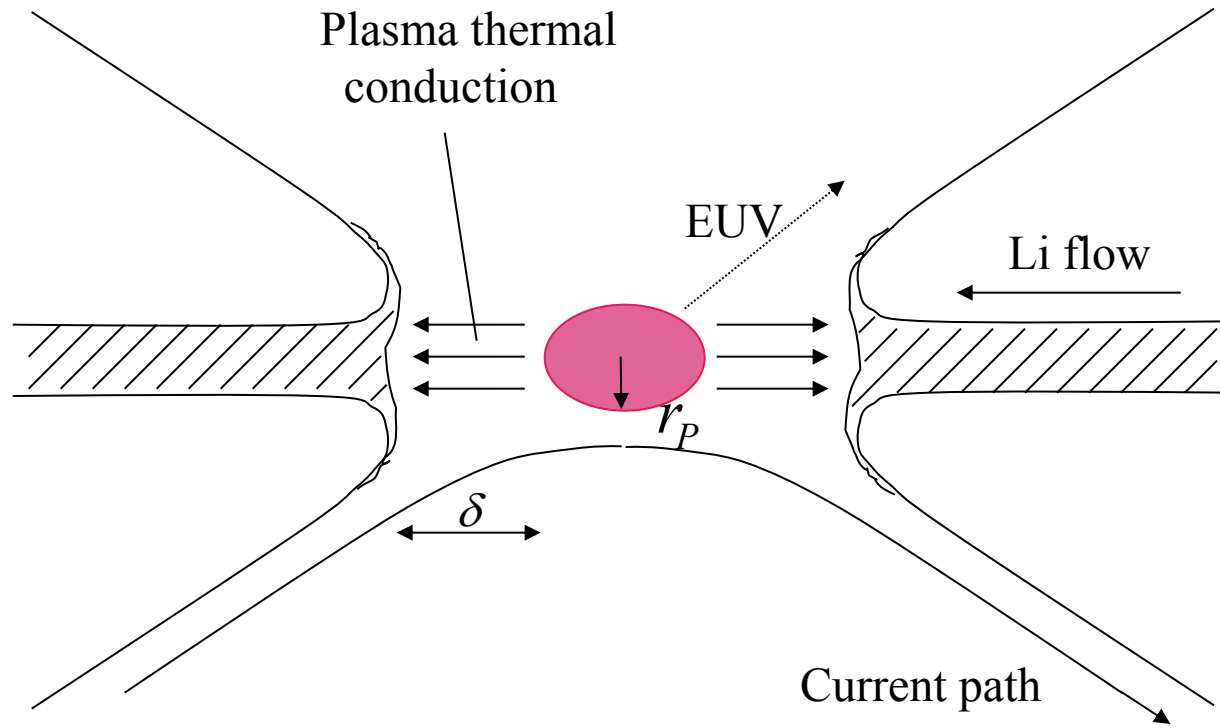
Heat flux Q is guided along axis by parallel B field.
Off axis, B_θ inhibits the heat flux

$$Q = \frac{\pi r_P^2\, 3.0 \times 10^2\, T^{5/2}(T - T_0)}{\delta \ln \Lambda} \ \text{Watts}$$

T =25eV, δ =0.1 cm => Q=60kW => E(3μs) = 180mJ/pulse/electrode

Lithium-wetted electrode tips: EUV heat load

Plasma thermal conduction

EUV

Li flow

r_P

δ

Current path
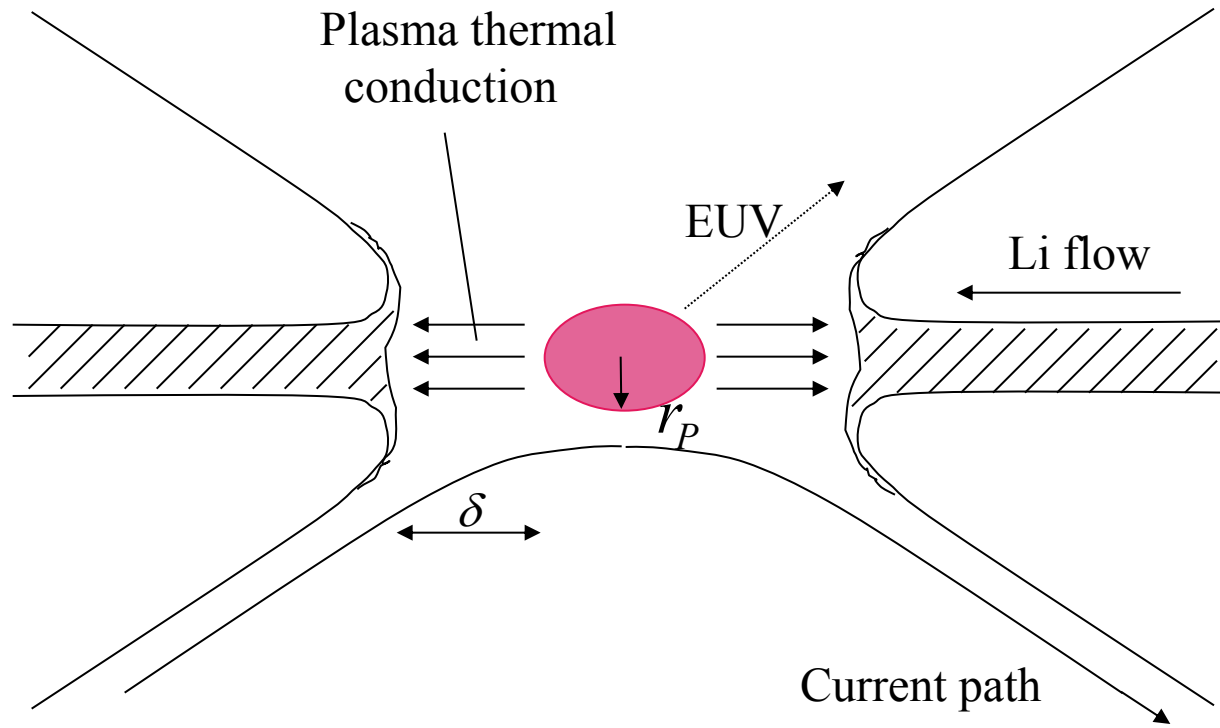
500W (IF) system can be built with individual Li lamps giving 500mJ

With 500mJ EUV in 2π, <u>EUV LOAD</u> = 150mJ/pulse/electrode

=> TOTAL 500mJ case energy load on tip = 180+150 = 330mJ/Pulse

Lithium-wetted electrode tips: demonstrated capability
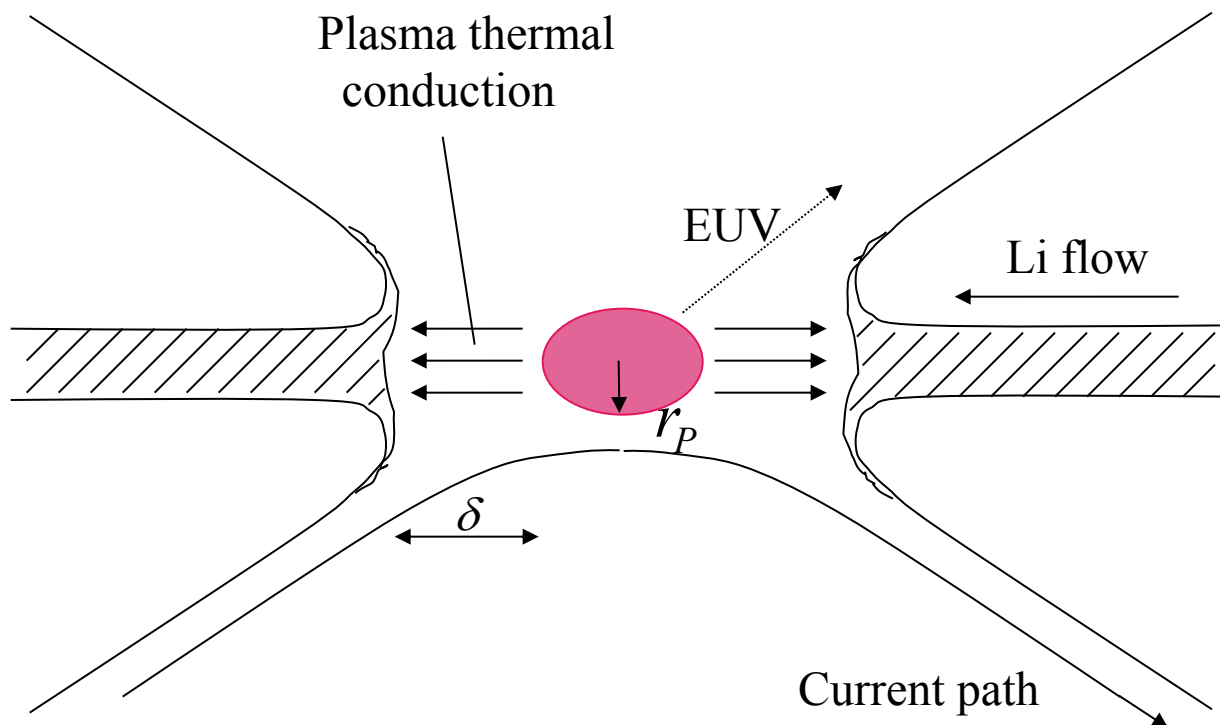
We have demonstrated Li flow with 3μsec pulses at 400Hz for >30minutes

Demonstrated 65mJ EUV from plasma at 25eV, i. e. total 200mJ/pulse/electrode

Steady state lithium flow handled 200/330 = <u>60% of 500W (IF) pulse requirement</u>

Lithium reflux rate supports electrode cooling up to 2kHz

Electrode

Area 'A'

**liquid
Li flow**

Condensation

Li vapor

Mid plane

Heat pipe cone

$$F_{Li} = \frac{A n_{Li} c_{Li}}{4}$$

Axis of rotational symmetry
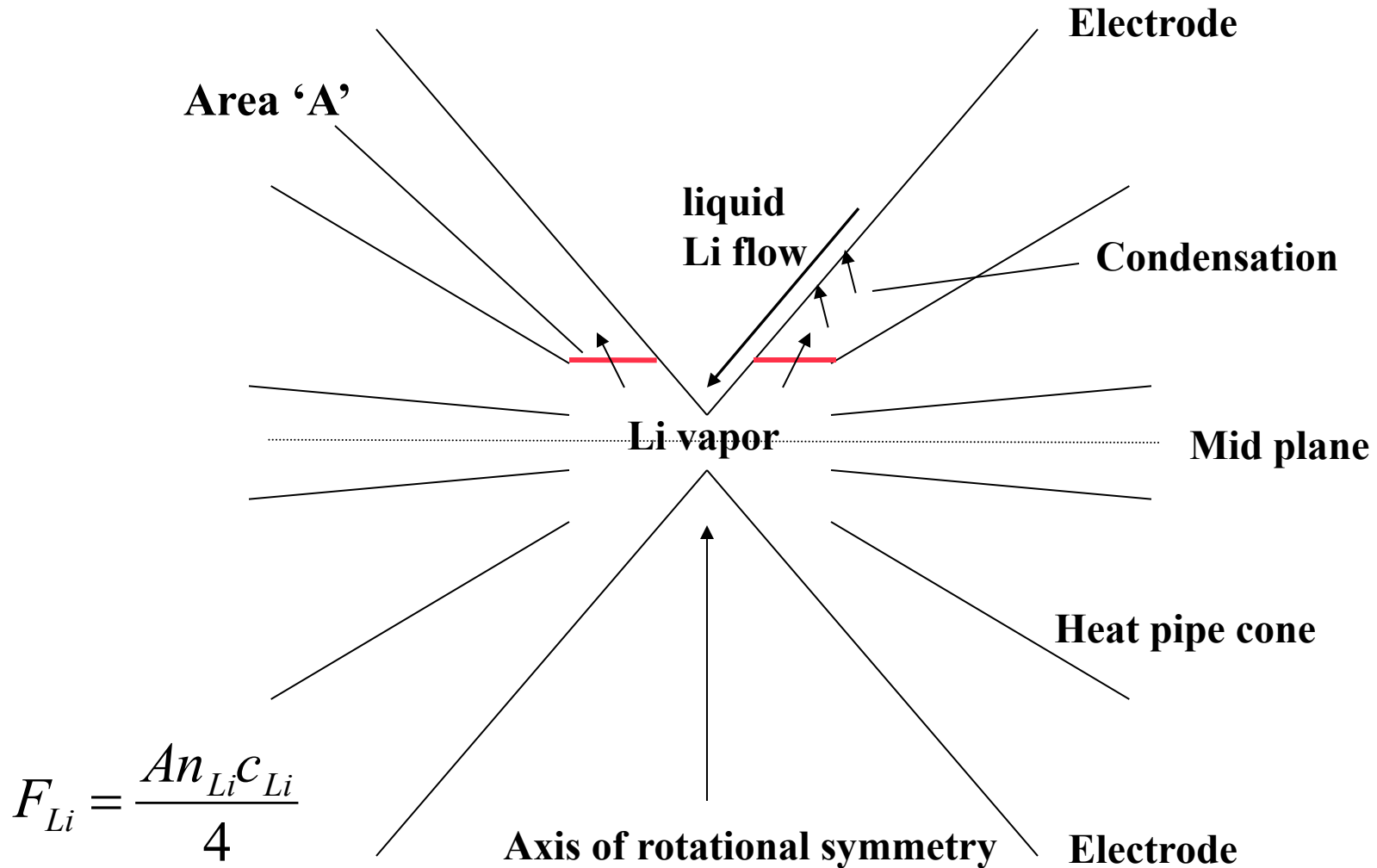
Electrode

=> Factor of 2 margin over the 1kHz, 500W needs

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Phase-Change cooling by partially-wetted surface

Limit on incident power in 3μsec pulse
for temperature impulse held to 2000K
using Tungsten properties at 2000K

Li

W

10μm

For functional phase-change cooling coverage:
roughness diameter < 10μm

Incident Power (kW mm^{-2})

Radius of dry area (μm)

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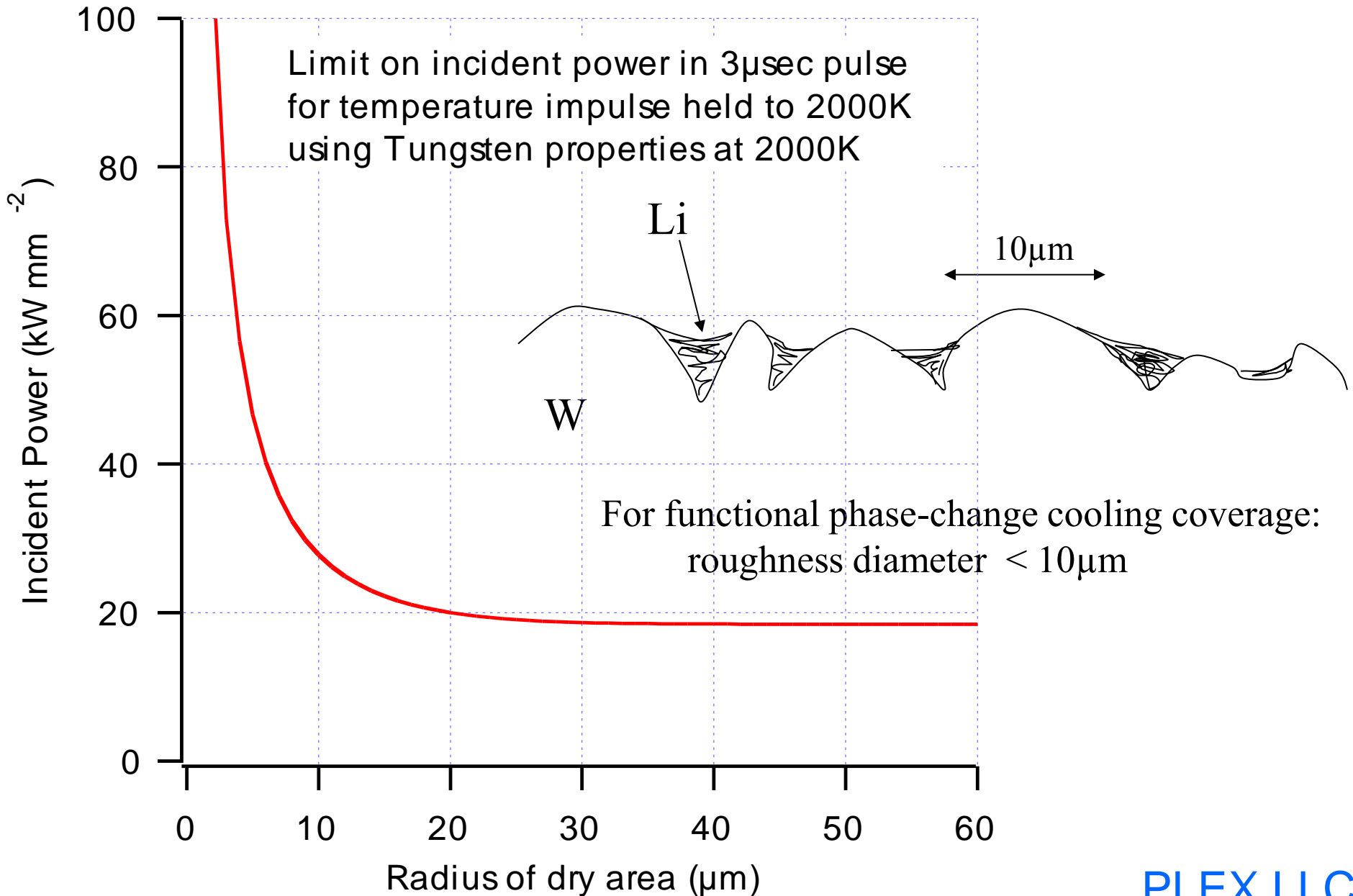
Status of electrode development

Electrode heat load, single pulse

Today, electrode tip heat <u>per pulse</u> >60% of 520mJ case because T = 25eV for 3μsec

Ratio of EUV emission to electrode heat input, per pulse, can be dramatically improved via shaped current

today's EUV waveform

improved waveform for 500mJ
(not to scale)

3μsec

$\leftarrow T$=25eV $\rightarrow$
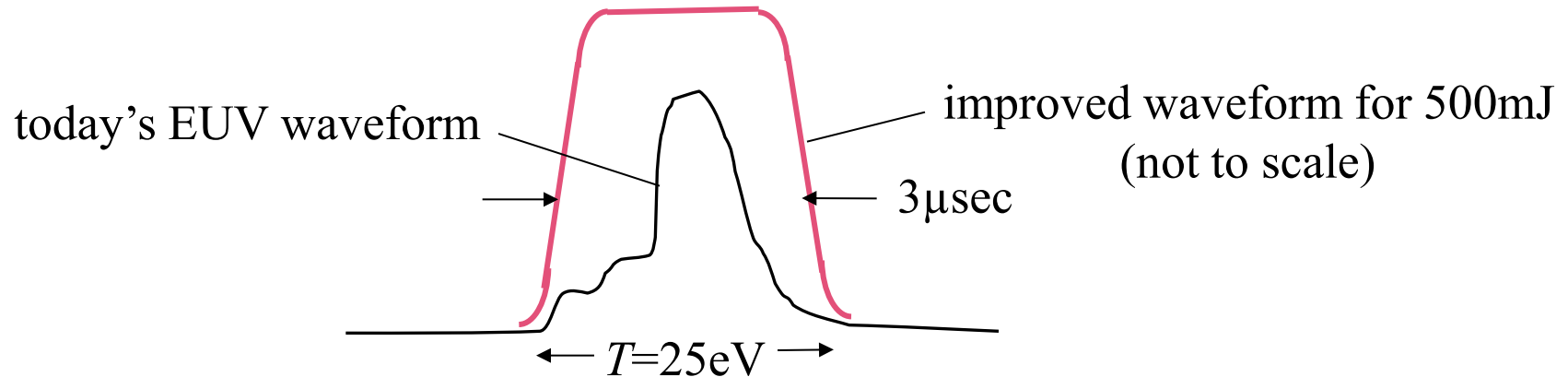
Electrode heat load at repetition rate

For 500W (IF) we need to scale from 400Hz today to 1kHz

Conduction cooling of electrode remote from tip can easily do this

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What Fast Ions?

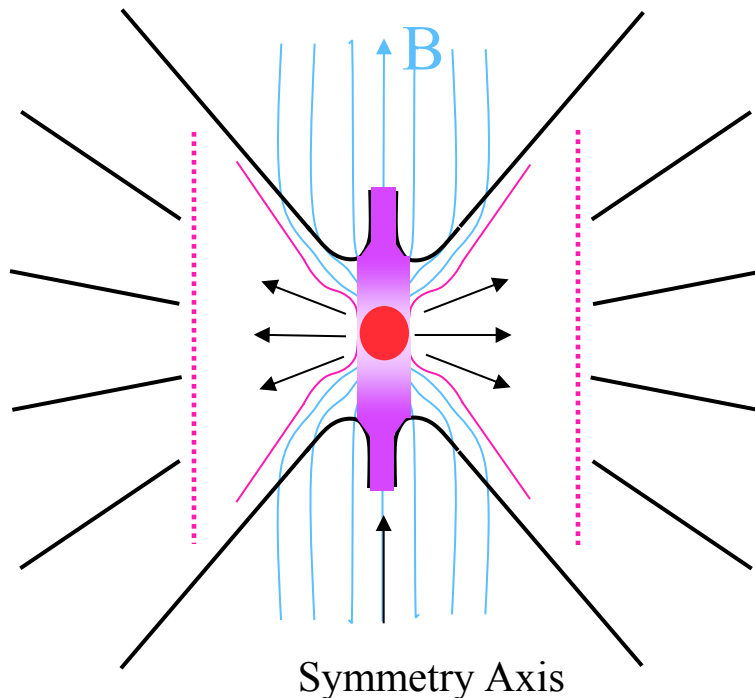**Unlike LPP, plasma dis-assembly is controlled by a current waveform**

Li pinch is 100x slower than tin pinch => energy of plasma is radiated during 1μsec (10^6sec^{-1}) controlled expansion and <u>no fast ions are generated</u>

$$R_{3B}(\text{sec}^{-1}) = \frac{1.8 x 10^{-8} Z^3 n_e^{\,2} \ln \Lambda}{T_e^{\,9/2}}$$

with T_e (K), n_e(cm^{-3})

=> Initial recombination rate > $5 x 10^7$ sec^{-1}

After recombination, radiation at $>10^9$sec^{-1} then plasma cools

B

Symmetry Axis

How to get the 500mJ needed for 500W (IF) system
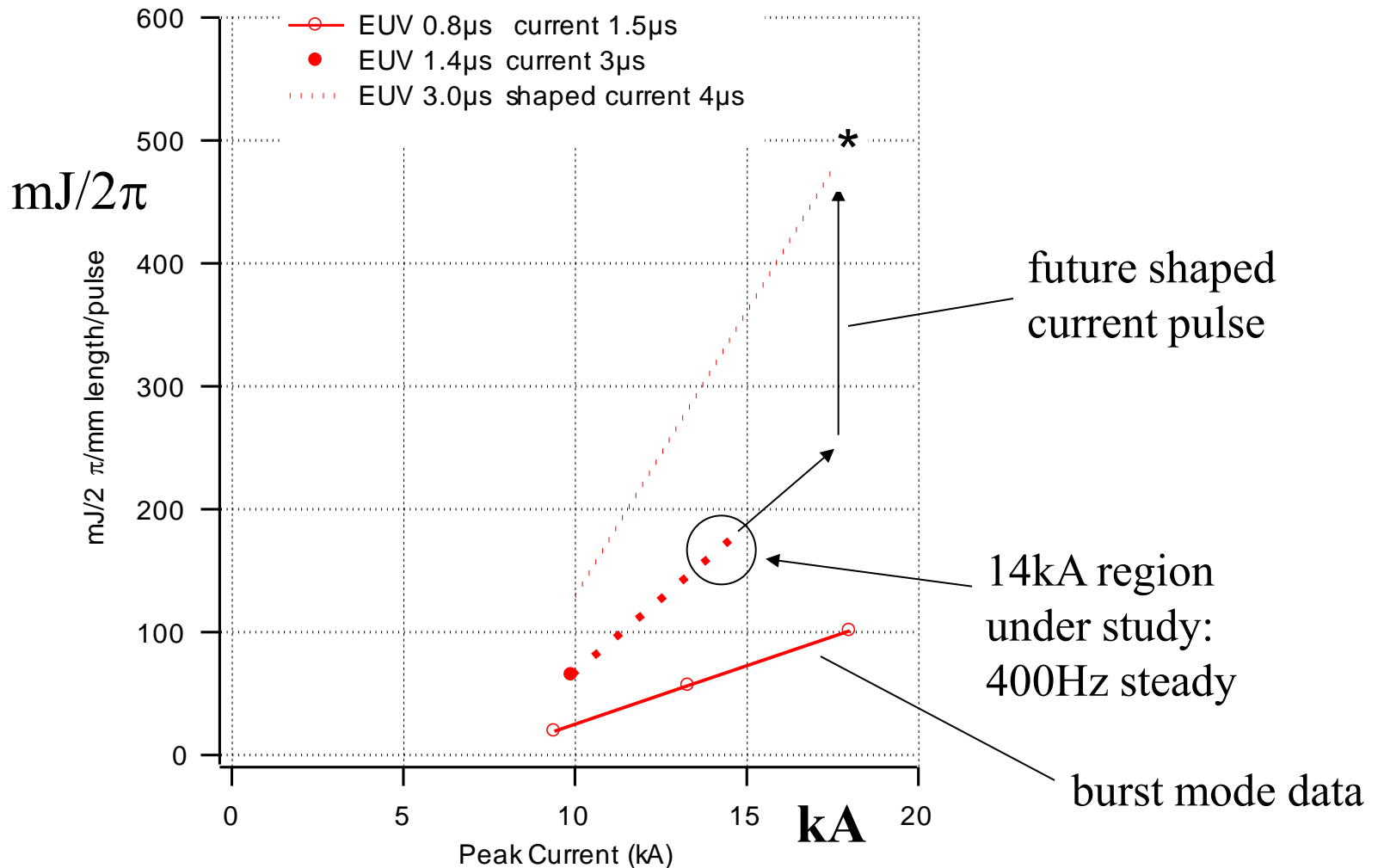
A. **More current, because at constant size, plasma density goes as I^2 and excitation power goes as I^4 (more Li also required, as I^2)**

B. **Shaped current pulse --> 3μs steady EUV**

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Physical Size of PLEX 500W class multiplexed Lithium EUV Source

Power Supplies, Controls
5m x 1m x 2m

Source/Condenser Module
diameter 2m, length 2m
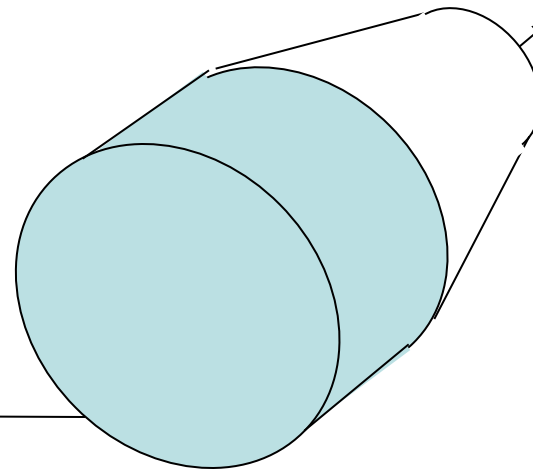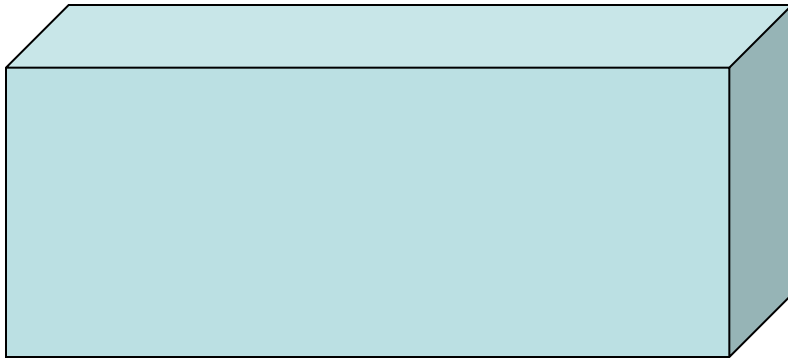
(Stepper)

Cost of Ownership:

Capital Cost

Individual Components

> **Lamp Head**
> **Helium barrier (pellicle)**
> **Collector**
> **Pulse Generator**

8-Fold Multiplexed Source

> **Chamber**
> **Vacuum Pumps**
> **Magnets**
> **Diagnostics, Controls**
> **Spinning Mirror System**
> **Assy. Checkout Labor**

Operating Cost

Refurbishment
Labor
Electricity

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Capital Cost (1)

Sale Price of Components in an individual lamp:

Lamp Head	$295K
Helium barrier	$150K
Collector	$500K
Pulse Generator	$105K
	——————
	$1,050K

Notes:

All prices include assembly and checkout labor

Lamp Head price is based on prototype costs at PLEX.

Helium barrier is a pellicle

Collector price is Media-Lario budgetary estimate for high volume production

Pulse Generator price is based on prototype costs at PLEX.

Capital Cost (2)

8-Fold Multiplexed Source, Common Items:

Chamber	$300K
Vacuum Pumps	$200K
Magnets	$60K
Diagnostics, Controls	$200K
Spinning Mirror System	$300K
Assy. Checkout Labor	$500K
	_____
	$1,560K

Full Capital Cost:

500W Lithium Source Sale Price $1,560K + 8 x $1,050K = $9,960K

Operating Cost:

Refurbishment	**a) Collectors $50K x 8 = $400K/year**
	b) Source components $200K/year
Labor	**$875K /year**
Electricity	**$105K /year**
	_____
	$1,580K/year

Notes:

Collector refurbishment is anticipated to be at 12month intervals. With lithium there is no erosion but high EUV flux may cause carbonization to a degree - hydrogen plasma cleaning will suffice

Electrode tip replacement each 1 billion pulses is assumed (<10mm component)

Labor assumes 1 person for full year, i.e. $100 per hour for 8,760 hours

Electricity necessary for 500W source is 120kW, priced at $0.10 per kW hr

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Summary (1)

1. Lithium can produce 13.5nm single line with theoretical η= 35%.

2. Experimental "slope efficiency" is already 20%.

3. Calculations predict 500mJ/pulse from 700µm plasma in 3µsec

4. Multiplexing at 1kHz of simple lamps at 500mJ, 1kHz each is proposed as the safest route to an 8kHz, 500W IF system

5. 46kW EUV to date is 26% of 175kW requirement (500mJ/3µsec)

6. 4X power gap will be bridged via 10kA -> 18kA increase as shown already in burst mode data.

7. Flat pulse shape will double EUV energy for same 25eV, 3µsec

Summary (2)

8. At 400Hz, assuming 8x mult., we now have 30W extrapolated to IF calculated with a conservative collection efficiency of 25% (fraction of 2π energy reflected to IF)

9. Electrode life $>>10^7$ with wetted electrode, may exceed 10^9

10. Phase-change cooling keeps tungsten tips far from melt.

11. Demonstrated thermal impulse is 60% of final 500W (IF) impulse

12. CoO Study => 500W (IF) for $10M and 120kW consumption.

A clear path to 500W IF has been described, based on data.

Supplementary Slides

Update on PLEX Patents relevant to lithium sources:

US Pat. #7,479,646
"Extreme Ultraviolet Source with Wide Angle Vapor Containment and Reflux",
issued Jan 20, 2009.

US Pat. #8,269,199
"Laser Heated Discharge Plasma EUV Source",
issued Sept 18, 2012.

US Pat #8,440,988
"Pulsed Discharge Extreme Ultraviolet Source with Magnetic Shield",
issued May 14, 2013

US app. #13/326,043
"Induction Heated Buffer Gas Heat Pipe for use in an Extreme Ultraviolet Source",
to issue 2013.

US application #13/775,663
"Lithium Extreme Ultraviolet Source and Operating Method", to issue 2013

US app. #12/854,375
"Z-Pinch Plasma Generator and Plasma Target", filed Aug 11, 2010.

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Lithium has fundamental "physics" advantages over tin

	Lithium	Tin
EUV (13.5nm) absorption cross section	2.1×10^{-18} cm^2	1.8×10^{-17} cm^2
EUV discharge production efficiency into 2π sr	>30% (>10% achieved)	3%
Spectral purity	single line	substantial out-of-band
"Debris" management	solved via heat pipe	complex and inefficient
Exhaust ion energy	<<100 eV	1-2 keV
Power scaling	multiplexed simple lamps @ N x 1kHz	single high power source plasma @ MkHz
Thermal transport	excellent	poor

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Engineering Path to >500W Li Source for HVM

Scientific proof of principle	← 2010
2,000sec continuous 400Hz	← We are here (x8 =>30W IF)
10,000sec continuous 1kHz	← 1.5 years away
Days continuous 1kHz multiplexed to >500W IF	← 3 years away

NOTE: "debris" problem already solved